Universidade de Aveiro Departamento de Ambiente e Ordenamento
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FLUXOS DE ÁGUA NO SOLO EM EUCALIPTAIS E PINHAIS DA ESCALA DA PARCELA A BACIA

RUNOFF GENERATION UNDER EUCALYPTS AND PINES AT THE TREE TO CATCHMENT SCALE

Ano civil da defesa: 2019

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenheira do Ambiente, realizada sob a orientação científica da Doutora Celeste Coelho, Professora Catedrática do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, e a co-orientação de Jan Jacob Keizer, Investigador Associado do CESAM – Centro Superior de Estudos do Ambiente e do Mar, Departamento de Ambiente e Ordenamento da Universidade de Aveiro, e António José Dinis Ferreira, Professor adjunto no departamento de Ciências Exactas e do Ambiente da Escola Superior Agrária de Coimbra, Bencanta.

Tese desenvolvida no quadro do Programa Doutoral em Ciências e Engenharia do Ambiente da Universidade de Aveiro, com o financiamento de uma bolsa de doutoramento (SFRH/BD/91690/2012) da Fundação para a Ciência e a Tecnologia (FCT), e o apoio dos projetos SILVAQUA - POCTI/MGS/49210/2002 e HIDRIA – PTDC/CTE-GEX/71651/2006, financiados pela Fundação para a Ciência e a Tecnologia (FCT).

Dedico este trabalho aos meus filhos Lucile e Yves que lidaram com filosofia com a minha falta de disponibilidade nos últimos meses da redacção da tese e cujo a energia e a alegria comunicativa me incentivaram a levar até ao fim esta tarefa.

o júri

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agradecimentos

Este trabalho foi realizado no âmbito de dois projectos de investigação científica e com a colaboração de um grande número de pessoas.
À Fundação para a Ciência e a Tecnologia, pelo financiamento dos dois projectos: Silvaqua (POCTI/MGS/49210/2002) e Hidria (PTDC/CTE-GEX/71651/2006).
Agradeço à Doutora Celeste Coelho por me ter acolhida de braços abertos na sua equipa há 20 anos atrás e ter me dado a oportunidade de fazer os meus primeiros passos na área da hidrologia, pelo apoio constante, a disponibilidade e o imensa carinho que sempre me ofereceu durante tantos anos de trabalho na sua equipa de investigação e na orientação da tese.
Agradeço ao Doutor António Ferreira, que me ensinou durante estes anos todos a pensar cientificamente, a ser crítica, a distinguir o essencial, e a consertar qualquer avaria de instrumentação no campo sem as ferramentas adequadas.
Agradeço ao Doutor Jacob Keizer pelo incentivo a dar continuidade a 10 anos de investigação, pela oportunidade que me ofereceu de investir tempo para me formar, pelo empenho e a amizade que colocou na co-orientação da tese.
Agradeço ao Sérgio e ao Óscar, pelo apoio incansável no campo sobretudo nas situações difíceis, no laboratório, na análise dos dados, pela profusão de teorias e ideias novas que argumentamos durante horas, e também pela afeição ao longo dos anos.
Agradeço à Maruxa, que sempre que foi preciso me apoiaram no trabalho de campo e na interpretação dos dados, que de simples colegas se tornaram excelente amigas.
Agradeço o companheirismo de Mitas que disponibilizou sem conta dados e tempo para auxiliar a redação da tese.
Agradeço à Isabel pela imensa paciência e perspicacidade que demonstrou na revisão da tese.
Agradeço a Carlos, pela promessa que ele me fez fazer de nunca desistir.
Finalmente, agradeço à minha família, em particular aos meus pais que apesar da distancia sempre estiveram presentem, e aos meus filhos Lucile e Yves que lidaram com filosofia com a minha falta de disponibilidade nos últimos meses da redacção da tese e cujo a energia e a alegria comunicativa me incentivaram a levar até ao fim esta tarefa.

Agradeço, igualmente, às instituições que contribuíram para a concretização deste trabalho. À Universidade de Aveiro, ao Departamento de Ambiente e Ordenamento, ao Centro de Estudos do Ambiente e do Mar da Universidade de Aveiro (CESAM). À Fundação para a Ciência e a Tecnologia (FCT) pelo financiamento prestado sob a forma de uma bolsa de doutoramento (SFRH/BD/91690/2012) e apoios associados

palavras-chave

escorrencia superficial, escoamento subsuperficial, escoamento da linha de água, eucalipto, pinhais, processos hidrologicos.

resumo

Existe um crescente reconhecimento entre ambientalistas, académicos e entidades públicas, da relação de interdependência entre as florestas e os recursos hídricos. Os serviços ambientais florestais são cruciais devido ao principal papel que desempenham na conservação e preservação do solo e dos recursos hídricos (ex. favorecem a infiltração e a percolação de água da chuva, que é armazenada no solo e recarrega os aquíferos). No entanto, as bases científicas e a dimensão da importância dessa relação entre a floresta e os recursos hídricos não são amplamente conhecidas e avaliadas.

Um conhecimento efetivo do ciclo hidrológico na floresta fornecerá uma melhor compreensão da relação entre a água e a floresta e levará a uma gestão mais racional e sustentável desses recursos naturais.

Atualmente, a floresta ocupa 35% do território de Portugal continental e desta, cerca de metade corresponde a plantações de eucalipto (26%) e plantações de pinheiros (23%). A monocultura de eucalipto aumentou drasticamente nas últimas décadas e levou a preocupações sobre possíveis implicações hidrológicas. Esta problemática será estudada no âmbito deste trabalho em varias bacias hidrográficas, localizadas na Serra do Caramulo.

O presente trabalho visa a quantificação e análise de padrões temporais dos diversos fluxos de água (escorrência superficial, escoamento sub-superficial e caudal) para duas bacias hinográficas, LOU e SDC, respetivamente dominadas por povoamentos florestais de pinhais e de eucaliptais.

Em termos de escoamento superficial, analisou-se (i) as diferenças globais entre os três ciclos de rotação sucessivos; (ii) os padrões inter-anuais dessas três rotações; (iii) a variação sazonal; e (iv) os principais parâmetros que influenciam a geração de escoamento superficial, com especial atenção para a dinâmica de humidade do solo. O estudo foi desenvolvido em diferentes escalas de trabalho (micro-parcelas de 0.28m2 e macro-parcelas de 16m2) e metodologias distintas (precipitação natural e simulação de chuva). O trabalho identifica ainda a relação entre a resposta hidrológica de duas bacias hidrográfica (eucalipto e pinheiro) e o tipo de uso do solo, a quantidade e a distribuição da precipitação e o teor de humidade superficial do solo. Finalmente, esta dissertação avalia a dinâmica global da resposta hidrológica da bacia florestal, integrando o estudo dos processos de escoamento superficial, fluxo sub-superficial e escoamento das linhas de água para identificar quais os vários processos ao longo do tempo e, em particular, com condições iniciais de humidade do solo contrastantes.

As principais conclusões deste estudo em termos de padrão de escorrência superficial, para um ciclo completo de produção de eucalipto são (i) as quantidades inter-anuais e anuais de escorrência superficial tendem a ser limitadas, tipicamente permanecendo abaixo de 10% da precipitação incidente; ii) o ciclo de rotação desempenha um papel determinante na geração de escorrência superficial, mas este papel foi mais percetível entre a primeira (R1) e a segunda (R2) rotação do que entre a segunda e a terceira rotação (R3); (iii) o método de medição influência os valores de escorrência superficial, mas a rotação R1 apresenta sempre maiores taxas de escorrência. A variação sazonal de escorrência segue a mesma tendência temporal em ambas as escalas de estudo (micro- e macro-parcelas), para as três rotações, indicando um aumento na quantidade de escoamento durante o período chuvoso e um aumento da percentagem de escorrência superficial durante a estação seca para R1 e R3 em ambas as escalas; (iv) os principais fatores na geração de escorrência superficial são o comprimento da parcela, a idade da plantação, a cobertura de pedra e cobertura de manta morta. O teor de humidade do solo é o principal fator que impulsiona o padrão temporal de escoamento superficial, relacionado com o aparecimento de característica de repelência do solo à água durante a estação seca, e a saturação do solo durante a estação húmida, levando à elevada produção de escorrência em apenas alguns eventos extremos.

Em termos caudal das linhas de água, (i) a quantidade anual de escoamento sofre grande variações inter-anuais, mais severa na bacia com pinhais LOU do que com eucaliptais SDC. (ii) Existe uma forte correlação linear positiva entre a quantidade de precipitação anual e a quantidade total de escoamento no rio (Q). (iii) O montante anual de evapotranspiração é relativamente constante ao longo dos seis anos de estudo e não é influenciado pelo valor total da precipitação. A quantidade de evapotranspiração média na LOU (907 mm) é significativamente superior à de SDC (739 mm). (iv) Apenas 15% do escoamento ocorreu durante o outono, contrastando com 30% do valor da precipitação correspondente ao coeficiente de escoamento de 23%. É durante o inverno, a estação mais

chuvosa (41% da precipitação anual) que a resposta hidrológica é mais importante, correspondente a metade do caudal anual e correspondendo a um coeficiente de escoamento de cerca de 67%. A humidade do solo influencia mais significativamente o coeficiente de escoamento de bacia com pinhais do que da bacia com eucaliptais. (v) O coeficiente de escoamento das linhas de agua para SDC e o coeficiente de escorrência superficial das plantações adultas (R2 e R3) presentem uma boa corelação, o que não é o caso para o coeficiente de escorrência superficial das plantações novas (R1)

O estudo de integração dos principais fluxos de água revela que (i) o fluxo sub-superficial é originado tanto pelo fluxo da matriz do solo quanto pelos fluxos em canais subsuperficiais (pipeflow) na interface solo-rocha. Os fluxos na matriz são gerados principalmente durante a estação húmida, enquanto os fluxos em pipeflow são exclusivos da estação chuvosa. (ii) O fluxo matricial está altamente correlacionado com a humidade do solo, tendo-se verificado um limiar de 25% de humidade do solo para uma profundidade de 40cm para início deste fluxo. (iii) O início do fluxo de pipeflow para humidade média do solo tem um atraso relativamente ao fluxo de subsuperfíciais da matriz. Começa com a saturação do fundo do solo, sem saturação de camadas mais superficiais do solo. O escoamento por pipeflow é influenciado pela intensidade da chuva. A resposta dos pipeflows à precipitação, quando em elevados teores de humidade antecedente, é quase instantânea, não requerendo a saturação do solo em profundidade. (iv) A resposta do escoamento nas linhas de água é altamente correlacionada com o comportamento do fluxo da matriz.

keywords runoff, subsurface flow, streamflow, eucalypt, pine, hydrological processes

abstract

There is an increasing recognition among environmentalists, academics and public agencies, that there is an interdependence relationship between forests and water resources. Forest environmental services are crucial since they play key roles in soil and water resources conservation (they favor infiltration and percolation of rainwater, which recharges soil and underground water storage). However, the scientific basis and importance of this relationship between forest and water resources are not widely known and evaluated.

An effective knowledge of the impact forests have on the hydrological cycle will provide a better understanding of the relationship between water and forest and lead to a more rational and sustainable management of these natural resources.

Currently, one third of continental Portugal is occupied by forest (35 % of territory). These forest areas are composed roughly by one quarter of eucalyptus (26%), one quarter of maritime pine (23%), one quarter of cork oak (23%), and the last quarter of essentially evergreen oak and stone pines (ICNF - IFN 6, 2010). Eucalypt monoculture increased drastically in the last decades and lead to concerns over possible hydrological implications.

This study aim to the description, quantification and temporal pattern analysis of water flows (overland flow, subsurface flow, streamflow) for two catchments LOU and SDC in the Caramulo mountains, dominated respectively by pine and eucalypt plantations.

In what concerns OLF we analysed (i) overall differences between the three subsequent rotation cycles; (ii) inter-annual patterns of these three rotation cycles; (iii) seasonal variation; (iii) key factors in OLF generation, with special attention on soil moisture dynamic and compare results for (iv) two plot scales (microplot of 0.28m2 and macroplot of 16m2) and two methodologies (natural rainfall and simulated rainfall). In addition, the work identifies the relationship between hydrological response of the 2 catchments (eucalypt and pine dominated) and the land use type, the rainfall amount and distribution and the superficial soil moisture content. The ultimate objective is to understand the global dynamic of the hydrological response of forested catchment, including the integration of overland flow, subsurface flow and streamflow processes, and to identify how these processes vary through time and, in particular, with contrasting antecedent soil moisture conditions.

The main conclusions of this study in term of overland flow (OLF) pattern, for a complete cycle of eucalypt production cycle are (i) multi-year and annual overland flow amounts tended to be limited, typically remaining below 10 % of the incident rainfall; (ii) the measurement method influenced OLF values, but the R1 plantation always presented higher OLF rates. Seasonal OLF rate followed the same temporal trend at microplot (mp) and macroplot (MP) scales for the 3 three eucalypt stands, showing an increase of OLF amount during the wet period and an increase OLF rate during the dry season for R1 and R3 at both scale. (iii) the key factors in OLF generation are plot length and plantation aging, stone cover and litter cover. Soil moisture content is the main factor driving OLF temporal pattern, related with the appearance of soil water repellence during the dry season, and soil saturation during wet season leading to high production of OLF concentrated in some few extreme events.

In what concerns streamflow behavior, (i) annual streamflow suffered large inter-annual variations, pine plantations presented larger variations than eucalypt plantations. (ii) There was a strong straight positive linear correlation between total annual rainfall (R) and total streamflow (Q). (iii) Annual evapotranspiration (ET) is relatively constant during the six years of study and not influenced by total rainfall. The average ET at LOU (pine) (907 mm) is strongly higher that at SDC (eucalyptus) (739mm). (iv) only 15% of the Q occurred during the autumn, contrasting with the 30% of annual rainfall amount corresponding to a runoff coefficient (RC) of 23%. It’s during the winter, the wettest season (41% of the annual rainfall) that the streamflow response is the most important, half of the annual Q flowed during this period corresponding to a RC of 67%. (v) Soil moisture content influence more significantly RC at the pine plantation than at the eucalypt plantation.

The study of subsurface flows (SSF) shows that (i) SSF is originated both by matrix flow and pipeflow at the soil-bedrock interface and is produce mainly during the wet season for matrix flow and exclusively during the wet season for pipeflow. (ii) Matrix flow presents a strong correlation with soil moisture content, a threshold of 25 % of soil moisture at 40cm deep is needed to start matrix flow, and saturation of the soil matrix is not required. (iii) Pipeflow initiation for medium soil moisture content is delay relatively to the matrix SSF. It starts with the saturation of soil bottom, without saturation of surface soil layers. Pipeflow discharge is influenced by rainfall intensity. Pipeflow response to rainfall input for wet soil moisture content antecedents, is almost instantaneous, starts prior to the matrix flow and doesn't require saturation of the soil bottom. (iv) Streamflow response is highly correlated with matrix flow behavior in time and intensity.

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Chapter 1

Introduction

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Introduction

There is an increasing recognition among environmentalists, academics, public agencies, that there is a relationship of interdependence between forest and the aquatic ecosystem, and that degradation or scarcity of one factor will disturb profoundly the existence and quality of the other.

Forests are characterized by distinctive sets of features and an exceptionally large variation of environmental conditions. Forest environmental services are crucial because of the key roles they play in conservation or preservation of soil and water resources (they slow water dispersion and favour infiltration and percolation of rainwater, which recharges soil and underground water storage)

However, the scientific basis and dimension of the importance of this relationship between forest and water resources are not widely known and evaluated. This results in some errors in term of expectation and even fragility of arguments in defence of an integrated management of these two resources, particularly with decision makers.

An effective knowledge of hydrological cycle in the forest will provide a better understanding of the relationship between water and forest and lead to a more rational and sustainable management of these natural resources.

Mediterranean headwater catchments have experienced major land-use changes in recent decades, mostly characterized by increasing natural vegetation and planted forests as a consequence of agricultural land abandonment (Beguería *et al.*, 2003, Debussche *et al.*, 1999, Lasanta-Martínez *et al.*, 2005). This trend could continue as the increasing demand for wood products and the growing pressures generate an increasing worldwide interest in the afforestation of unproductive lands with fast-growing tree species (Lafleur *et al.*, 2013). FAO (2001) predictions indicate that plantations will cover 5 to 10% of the world's forested land area and that close to 50% of commercially harvested wood will come from these plantations. On the other hand, global climate change could lead to a much drier climate in the Mediterranean basin (Giorgi & Lionello, 2008), therefore threatening those existing forests that are highly sensitive to the region’s strong aridity gradient. Both large-scale afforestation and deforestation can have major impacts on the hydrological cycle (Zhang *et al.*, 1999). This highlights the importance of a detailed process-based understanding of the relationship between land use, and especially forests, and the water balance in this region.

In particular, land use is one of the most important factors controlling the intensity and frequency of overland flow, due to differences in surface storage, soil infiltration capacity or soil properties, that change the partitioning between infiltration and surface runoff (Nunes *et al.*, 2011). However, land use not only alters surface runoff processes but can also affect subsurface flow (Latron & Gallart, 2008, Peters *et al.*, 2003).

Portugal is an illustrative case-study for Mediterranean afforestation. It is the European country where the transition from deforestation to reforestation was quickest (Pereira *et al.*, 2009). The forest area was 4-7% of the Portuguese continental area in 1870 and, over a century, increased to more than 30% (Pereira *et al.*, 2009). The afforestation plan supported the planting of 420.000 hectares of tree stands from 1938 to 1977, in particular with *Pinus pinaster* Aiton and later *Eucalyptus globulus* Labill (Baptista, 1993, Coelho, 2003, Jones *et al.*, 2011). The production of eucalypt in the coastal region of Central and North Portugal is now double that of pine (Soares *et al.*, 2007). Between 1995 and 2010, eucalypt plantations in Portugal increased considerably at the expense of pine plantations and, in by 2010, were the dominant forest type, occupying 812.000 hectares or 26% of the Portuguese forest cover (ICNF, 2013). Despite these large land-use changes and the widely-acknowledged relevance of forests for the overall availability of water resources in Portugal, the impacts of afforestation on the hydrological cycle continue to be poorly quantified (Pereira *et al.*, 2009).
Moreover, climate projections for the study region foresee a pronounced decrease in precipitation, especially during the warm season, and a pronounced warming, with a maximum in the summer season. The inter-annual temperature variability is expected to increase, especially during summer, leading to a more frequent occurrence of extreme temperature events (Giorgi & Lionello, 2008, Nunes *et al.*, 2013, Räisänen *et al.*, 2004, Sanchez *et al.*, 2004). In turn, these predicted changes in climate will have noticeable effects on surface and ground water resources (Nunes *et al.*, 2013, Stigter *et al.*, 2012) and, thus, on water-related ecosystem services in the affected areas (Aguiar *et al.*, 2009).

1.1. Forest

1.1.1. Forest history in Portugal

Currently, one third of continental Portugal is occupied by forest (35 % of the territory). These forest areas are composed roughly by one quarter of eucalyptus (26%), one quarter of maritime pine (23%), one quarter of cork oak (23%), and the last quarter of essentially evergreen oak and stone pines (ICNF - IFN 6, 2010).
The Portuguese forests differ from those of Europe, as they fundamentally plantations of trees rather than forest.

In fact, natural forest suffered, during the last centuries, from demographic and technologic human development. The demographic expansion led to the increase of agricultural land to permit the development of pastoral and agricultural cropping systems as well as an increase in demand for timber for cooking or heating, resulting in large scale deforestation. Technological development also led to an increasing need for wood, including during the maritime exploration period, oak for the maritime fleet construction. The beginning of the industrial revolution also contributed to accelerate the deforestation phenomenon in order to provide raw material and energy to a growing number of factories (Alves et al., 2007).

Political actions were taken at different times to reverse this trend. The measures aimed to protect resources (soil and water conservation) and to satisfy timber demand. For example, in the 13th century, the afforestation of the coastal pine forest "Pinhal de Leiria" ordered by D. Afonso III, was one of the first forests planted in the world. Some centuries later, the Tree Law was promulgated in 1565 and instituted the planting of uncultivated lands and commons "*baldios*" with autochthones species (Alves et al., 2007).

Nevertheless, by the end of the 18th century, Portugal was suffering from an acute depletion of forest resources. In 1875, the forested area in Portugal was only 7% of the territory with about 670 mil ha in total, comprising 370 mil ha of "*montado*", 210 mil ha of pine and 50 mil ha chestnut and oak forest (PNDFCI, 2012).

At the end of the 19th century, faced with the forest disappearance from many mountain areas and increasing timber needs to support industrialization development, new forest policies and strategies were developed in order to inverse the tendency and supply the increasing demand for wood and provide technical resources and Forest Services to support afforestation.

1.1.2. Pine afforestation

The maritime pine was the pillar specie of the afforestation. *Pinus Pinaster* is a resinous specie native to the Mediterranean Occidental Region and North Africa, with a coastal distribution (principally Southwest Atlantic coast of Europe and occidental Mediterranean), related to its affinity for well-drained soil (Correia et al., 2007).

Nevertheless, it can also be considered as a pioneer specie in term of ecological succession. It is a very rustic tree that possesses a high capacity to survive and develop in very degraded areas. It contributes to improved soil quality by increasing soil organic matter content, and then permits the appearance and development of other species. It is also a fast-growing specie, with a high germination potential leading to a fast natural expansion, providing large quantity of quality timber with high economic value. *Pinus Pinaster* presented all the requirements to be the preferred specie for Portugal afforestation (Correia et al., 2007).

At the beginning of the 20th century, the expansion of the maritime pine was moderate and pine forests covered about 250 mil ha. During the 3 first decades of the XX century, the expansion of forest pine was maximum, reaching about 1.130 mil hectares in 1930. This expansion funded its origin principally, not in public effort as commonly referred, but in private initiatives of converting uncultivated lands in productive forested areas.

The afforestation plan which started in 1938, involved the plantation of 420mil ha in 30 years.

The area occupied by pine and other resinous species increased from 210 mil hectares in 1874 to 1380 mil hectares in 1978.

Since 1980, however, the pine area began to decline. The last National Forest Inventory estimated maritime pine area to be about 714 mil ha, a decline of nearly 50% in 30 years.

The most frequent reasons evocated for its decline are the large burned area, lack of good management, concurrence of more economically competitive species and more recently the nematode attack. These factors led to strong decrease of the pine forest, abandoned and colonized by shrub "*maquis*" areas after recurrent fires or substituted by eucalypt plantations, much more productive and economically lucrative especially in the short term (Mendes, 2007).

1.1.3. Eucalypt afforestation

Eucalyptus (*E. globulus Labill*) is nowadays the principal specie with economic interest cultivated in Portugal. It is an exotic tree that occurs naturally in Tasmania and in the SE Australia. Nowadays, Portugal is the largest producer of *Eucalyptus Globulus* in the world, it represents 31 % of worldwide plantation area (GIT Forestry Consulting, 2004).

Eucalyptus was introduced in Portugal in the mid-nineteenth dle of the century, as an ornamental tree. Nevertheless, the emergence of a fast-growing tree species, in a country suffering of a chronic lack of wood was a great opportunity and an effective way to provide timber for farms use and fuel.

Since 1940, eucalypt area underwent an impressive expansion, roughly parallel to the growth of the pulp industry. The eucalypt area expanded by a factor of almost fourteen in only 50 years, from 58 mil hectares in 1956 to about 812 mil ha in 2010 at the last National Forest Inventory and overtaking the cork oak forest, emblematic specie of Portugal. Nowadays, eucalypt occupy 8% of the Portuguese territory and 26% of the forest area. Eucalyptus are very well adapted to the soil-climatic characteristics of Portugal and its spatial distribution follows the ecophysiological preferences of the species. Eucalyptus needs annual precipitation of over 700mm and mild temperatures without frost. At present, the plantations occur predominantly in the costal parts of the country, particularly in the costal central region. Eucalyptus production for coastal center region is around 20t/ha/year (16 to 24), the productivity varying with to 2 factors: climate and soil fertility (Pereira, 2007).

In 1953, in the Baixo Vouga region of north-central Portugal, the first paper pulp factory opened in Cacia, at the foothill of the Caramulo Mountain. Boosted by this paper pulp industry, forests occupy now half of the region, of which 2/3 is covered by Eucalypt plantations (ICNF, 2013; IFN6).

In many aspects *Eucalyptus globulus* responds to the need of the country. It is particularly well adapted (Goes, 2014):

- to paper pulp production, its trunks represent a really high quality raw material with technologic characteristics adapt for paper pulp and then follow the expansion of this industry in Portugal;
- to the climatic and soil conditions of Portugal and attain high productivity rates in many regions of the country (especially central region);
- to intensification, either through improvement of silvicultural techniques or improvement of plants nursery or genetic improvement;
- to the complicated economic situation of the country, growing fast it became a quick and easy source of income for many families;
- to rural abandonment, very resilient and growing without any constraints cultural exigencies;
- to forest fire, re-sprouting naturally from trunks after cutting.

Eucalyptus Globulus is a technological, socio-economic success very important for the national economy. In 2015, forest-based industries accounted for 9.4% of national exports, and pulp and Paper exportation represented 53% of this forest sector exporting to more than 130 countries. Spain, France and Germany are the main destinations of exports in the forestry sector.

The contribution of the forest-based sector to employment is also relevant representing in 2010, 1.4% of the employed population in Portugal. It is also an important source of remuneration for more than 400 thousand private forest owners and especially relevant in regions of the interior of the country where the availability of sources of alternative or substitutive remuneration is important to mitigate the depopulation of the territory (AIFF, 2013).

Even if Eucalypt plantations are very controversial in term of ethic (introduction of exotic species) and socio-cultural aspects and with negative effects on landscape, on soil, on water resources, on biodiversity and ecosystem dynamic, on wildfire risk, the economic interest of this specie is a fact and this fact exceeds all negative aspects, whatever individual or political level, leading to the continuance of eucalypt expansion in Portugal.

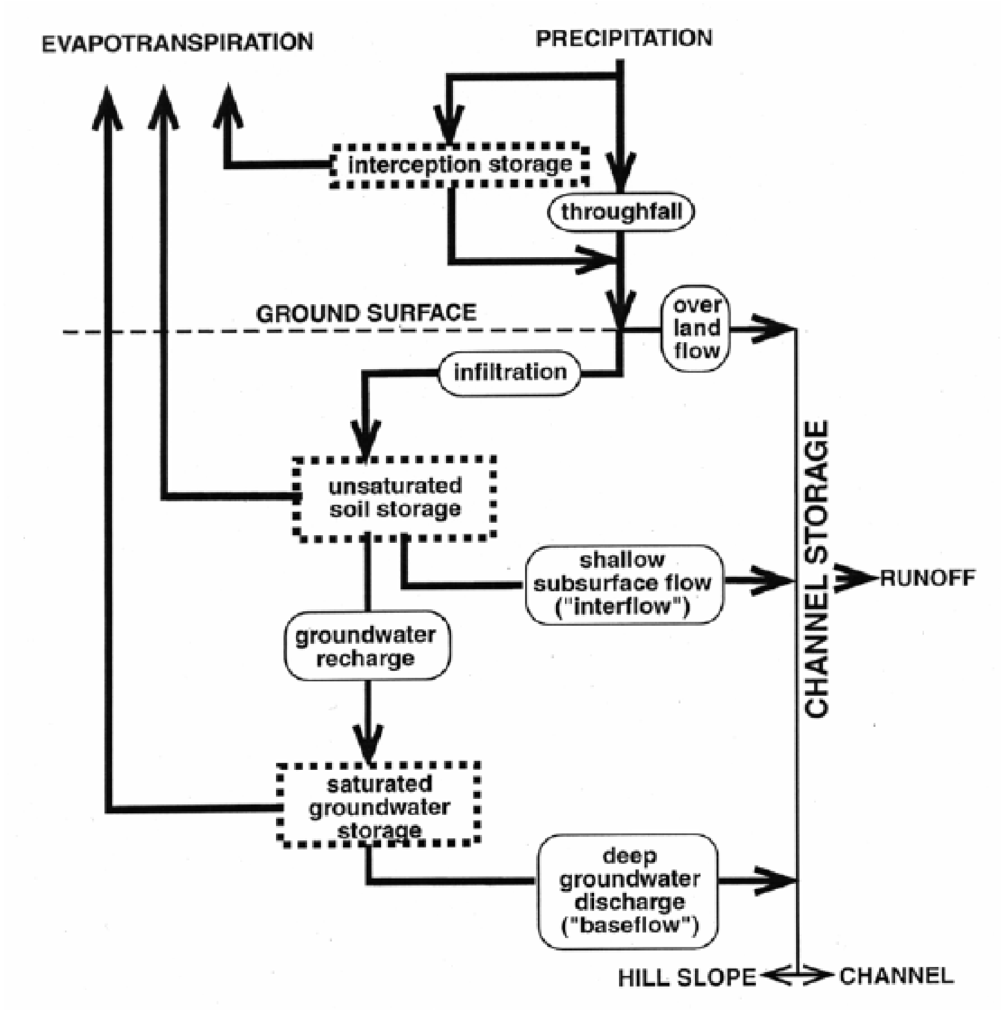
1.2. Runoff processes – Water paths on the hillslope

Hillslope hydrology is concerned with the partition of precipitation as it passes through the vegetation and soil between overland flow and subsurface flow. Since the pathways followed by the flow can attenuate and delay the flow to different extents, it is important to know all those relevant mechanisms (Kirkby, 1988). Thus during a storm event, one part of the rainfall is intercepted by vegetation and litter layer, another part runs off directly on the surface as overland flow and the remaining water infiltrates into the ground where many different flow paths exist, which move at different velocities before attaining the river. The response of a river to intense precipitation can be strong and immediate or moderate and retarded depending on the proportion of overland flow and which flow paths the infiltrated water takes.

A schematic view of the alternative fates of precipitation on a hillslope is presented in the figure 1 adapted from Kirkby (2002).

The dominant flows at plot scale or at hillslope scale, for a storm event, tend to be infiltration and runoff and they will be presented in detail in the next section. Interception plays an important role in term of mitigation of the rainfall amount reaching the soil and will also be presented in the next section. In general, transpiration is a phenomenon taking place throughout the year and representing a large part of the hydrological balance, nevertheless considering a storm event study, over a few hours, transpiration becomes negligible.

Interception at these scales essentially involves a delay in the response of the soil because the canopy and litter layer store water. The interception depends mainly on the vegetation cover and the dynamics of the rain. Discontinuous rain will cause more interception than continuous rain of the same duration and volume (Musy and Higy, 2004).



CHAPTER 1

***FIGURE 1.** RUNOFF PROCESSES --- THE PATHS OF WATER ON THE HILLSLOPES. A SCHEMATIC VIEW OF THE ALTERNATIVE FATES OF PRECIPITATION ON A HILLSLOPE (LECTURE SECTION 6, HILLSLOPE HYDROLOGY, KIRKBY 2002)*

1.2.1. Interception

Tree canopy and litter layer reduce significantly the amount of precipitation that reaches the soil. The importance of interception depends mainly of storage capacity, precipitation characteristics and potential for evaporation.

(i) The storage capacity, well known and studied, is often considered as the most important feature in interception processes. This is especially true for litter layer which has a reduced evaporative demand due to the absence of wind at ground level.

(ii) The precipitation characteristics. Although the severity of the rainfall event will influence the interception rate, it’s mainly the temporal distribution of the rainfall events that will determine this amount. The number of rainy days per month or the number of

rainy months per year are ones of the most sensitive parameters in the calculation of the interception.
(iii) The evaporation potential will determine the maximum flow of interception. In temperate climates, the evaporative potential is often the limiting factor. This factor is usually much higher at the tree canopy level than at litter layer, much less exposed to the wind.
Although interception reduces the amount of incident precipitation it also acts as a threshold process that will cause a delay in subsequent processes, such as infiltration and overland flow. These processes may only occur after the storage capacity of the plant cover and the litter layer are exceeded. This storage capacity represents a key factor in controlling interception by tree canopy (wood and leaves) and litter layer. Although the storage capacity of the litter layer is generally higher than that of the tree canopy, the interception of the tree canopy is greater, which highlights the importance of the evaporation potential, much higher for the tree canopy with direct exposure to solar radiation and wind.

According to Rutter et al. (1975) tree canopy interception can vary from 12% of precipitation to a forest of defoliated oak trees up to 48% for a spruce forest. Bryant and al. (2005) determined similar values for various forest types in the United States from 17 to 22% interception. In South America, Schellekens et al. (1999) recorded a 50% interception rate for a tabonuco forest.
For Mediterranean forests, evaporation from canopy interception is an important component of water use. Interception rates have been found to vary widely, depending on the tree species, canopy density, and climatic conditions. With respect to *Pinus pinaster*, Ferreira (1996) reported interception rates of 15-18 % in the Águeda watershed of north-central Portugal, while Valente et al. (1997) found similar rates of 17 % in a drier region of central Portugal (600 mm/yr precipitation). For *Eucalyptus globulus*, Ferreira (1996), Valente et al. (1997) and Coelho et al. (2008) observed lower rates, amounting to 10-14 % and 11 % and 9%, respectively.
However, Interception in general is not always considered as a significant process when, for example, modeling the surface runoff associated with the precipitation, or is simply considered as a fixed percentage of the precipitation.
In general, interception studies focus on canopy interception and pass over interception at ground level. Nevertheless, Gerrits et al. (2007) showed that precipitation interception may double, taking into account litter interception. The major difference between tree canopy and ground surface interception is the relatively low storage capacity of the tree canopy compared to the soil surface. On the other hand, the tree canopy has a much higher evaporation potential compared to that of the soil surface (Baird and Wilby, 1999)

Despite the importance of litter layer, fewer information is available regarding the dynamics of moisture at the soil surface. This gap can be attributed, in part, to the difficulty of studying this phenomenon *in situ*. (Putuhena and Cordery, 1996; Schaap et al., 1997; Tobon-Marin et al., 2000).

1.2.2. Surface Flows

The surface runoff or overland flow reaches the rivers rapidly and has awakened and dominated hydrological knowledge (Ward, 1984). It is possible to subdivide the surface runoff according to the process that originated it: the overland flow due to the excess of the infiltration capacity of the soil (infiltration excess overland flow or Hortonian overland flow) and overland flow due the runoff of direct precipitation that reached a saturated soil surface (saturation overland flow)

1.2.2.1. Infiltration Excess Overland flow

For decades, the ideas of Horton dominated the general perception of runoff formation. Horton (1933) supposed that floods are formed mainly by overland flow from areas with limited infiltration capability.
The infiltration-capacity was defined by Horton (1933) as "the maximum rate at which a given soil can absorb rainfall when the soil is in a specified condition." It also recognized a maximum and a minimum infiltration capacity. For a given soil, the infiltration-capacity varies between a maximum value when the soil is dry and a minimum value after wetting and packing. The infiltration capacity is generally close to the maximum during short storms following dry periods and close to the minimum during prolonged wet periods."
The infiltration excess overland flow appears when the rainfall intensity exceeds the maximum capacity of the soil to absorb the water. This soil infiltration capacity decreases over time until it reaches a constant value (references). The reduction of the soil infiltration capacity can be attributed to: (i) soil compaction by the action of the droplets, which reduces the size of the pores, (ii) the filling of the interstices of the soil by small particles carried by the rainwater, and iii) reduction in the capillarity suction forces as pores get filled. The overland flow then happens when the infiltration capacity becomes lower than the precipitation intensity. The overland flow is then represented by the difference between the precipitation and the soil infiltration capacity.

The evaluation of the importance of the infiltration process will allow to determine the fraction of the precipitation that will participate in the surface runoff and which fraction will participate to the subsurface flows and the recharge of the underground sheets.

The infiltration excess overland flow is considered relevant to explain the hydrological response of hydrological basins located in semi-arid zones (Albergel et al., 2003) and for situations of high intensity rainfall events. Nevertheless, it is also assumed that soils with high hydraulic conductivity in temperate or humid areas may have a lower infiltration capacity than the maximum precipitation intensities recorded. It also happens in temperate regions at altered areas (by fires, crust, soil water repellence) where infiltration capacity is reduced.

In general, however, it is rare to observe this type of overland flow in temperate regions with natural or semi natural vegetation and in many areas of afforested land-use, where the soil infiltration capacity is generally high. Several studies have shown (Hewlett and Hibbert, 1967; Jordan, 1994) that in these regions flood formation occurs with rain intensities lower that soil infiltration capacity.

1.2.2.2. Saturation Overland flow

An alternative to the Horton theory was proposed by Hewlett and Hibbert (1967) who showed that even for heavy rains, all precipitation in the upper parts of the basin infiltrated into the soil, increasing locally soil moisture content. This water is transferred to areas further downstream by the lateral flows (throughflow, pipeflow or groundwaterflow) and so formed in the vicinity of the watercourses or in the valleys a layer saturated to shallow depth.

The runoff on saturated surfaces then occurs when the soil's capacity to store the water is exhausted and when the ability to transmit the flows laterally is exceeded. Thus, the water can no longer infiltrate and precipitation incident will flow on the surface of the soil.

Kirkby and Chorley (1967) present several factors that can lead to the appearance of saturated soil surface conditions: (i) the concavity of runoff lines downstream where, in the convergence zones of the lateral subsurface flows, the ability to transmit the flows laterally is overcome, and causes saturation of the superficial part of the soil; (ii) The concavities found in the slopes, in which the decrease of the hydraulic gradient will favor the saturation of the soil at the surface, at the base of the concavity; (iii) Areas that present a decrease of thickness of the superficial horizons; the finer soils have a weaker flow retention and transmission capacity which can lead locally to the formation of a saturated area to the surface; (iv) Areas with little slope may not present a sufficient hydraulic gradient to drain the water that infiltrates and accumulates in the soil when a prolonged rainfall event occurs or of great intensity.

At proximity to a perennial stream. In such slope-base location, saturation or near saturation areas are more common. Generally, soil moisture content increases continuously down the length of a slope and approaches saturation commonly only in a zone immediately marginal to the stream channel, although this zone of saturation will

extend upslope as the storm continues. Overland flow will occur when soil water draining down the slope is forced to the surface by the complete saturation of the soil lower down the slope, and this condition is usually present only near the base of the slope. Dunne and Black (1970) paper present a better understanding of near-stream saturation overland flow as a variable source concept dynamic, that described clearly the Variable Source Area Concept. In the upland watersheds of Vermont, USA, the major portion of storm runoff seems to be produced as overland flow on small saturated areas close the stream.
The saturated area contributing to overland flow production is dynamic in the sense that it may vary seasonally or throughout a storm, and is basically an expanded stream system. The fluctuation of this partial area can be related to geology, topography, soils, antecedent moisture and rainfall characteristics.

1.2.3. Subsurface flows

1.2.3.1. Throughflow

Lateral subsurface flows are a significant component of the catchment hydrology. The essential condition for the appearance of throughflow is that the hydraulic lateral conductivity of the environment has to be superior to the vertical conductivity. It is generally assumed that this type of flow takes place when a saturated zone has formed above an impermeable or less permeable subsurface horizon (soil-bedrock interface or less permeable soil layer). Water then flows laterally in the soil, in the direction determined by the soil-bedrock interface slope (or less permeable layer). It is possible to form several overlapping levels of throughflow corresponding to changes in soil structure and / or texture.

While throughflow initiation is relatively well described at a point, few studies have quantified the development of subsurface saturation and subsurface flow initiation spatially across the entire hillslope (Tromp-van Meerveld and McDonnell, 2006a). The fill and spill hypothesis asserts that during a rainfall event, throughflow initiation occurs only when the bedrock depressions are filled and the water level in these depressions rises high enough for water to start spilling over the bedrock microtopography. (Figure 2). This hypothesis explain that the bedrock micro topography is responsible for the observed precipitation threshold for significant subsurface stormflow to occur (Tromp-van Meerveld and McDonnell, 2006b).

The role of matrix flow is problematical. Hewlett and Hibbert (1967) originally envisaged that the sideslope delivery of moisture to a water table at the foot of slopes was through the soil matrix by a piston-type flow (Goel et al., 1977) mechanism, which they termed 'translatory flow'. It is now generally accepted that the occurrence of lateral subsurface

stormflow via matrix flow is too slow to produce significant volumes of quickflow (Kirkby, 1988) without the assistance of some other mechanism.
The path by which subsurface stormflow is delivered to streams can be viewed as routing through the soil matrix (matrix flow), macropore flow and pipeflow.

Preferential flows (macropore and pipeflows), become prevalent under conditions of intense rainfalls and low matrix potentials (Germann, 1986), and can occur simultaneously with piston flows (the displacement of pre-existing water in the soil matrix) in heterogeneous soils (Bonell, 1986).

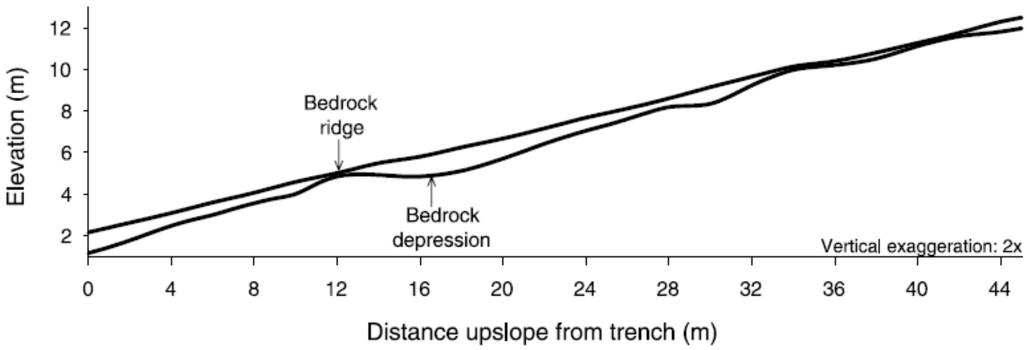


FIGURE 2*. SURFACE AND BEDROCK TOPOGRAPHY ON A REPRESENTATIVE UPSLOPE TRANSECT ACROSS THE SLOPE (TROMP-VAN MEERVELD AND MAC DONNELL, 2006)*

1.2.3.2. The flow of water through macropores

The presence of macropores close to the soil surface or deeper in the soil profile is important in the processes of water fluxes. Figure 3 offers one simplified view. Three stages of flow may be expected.

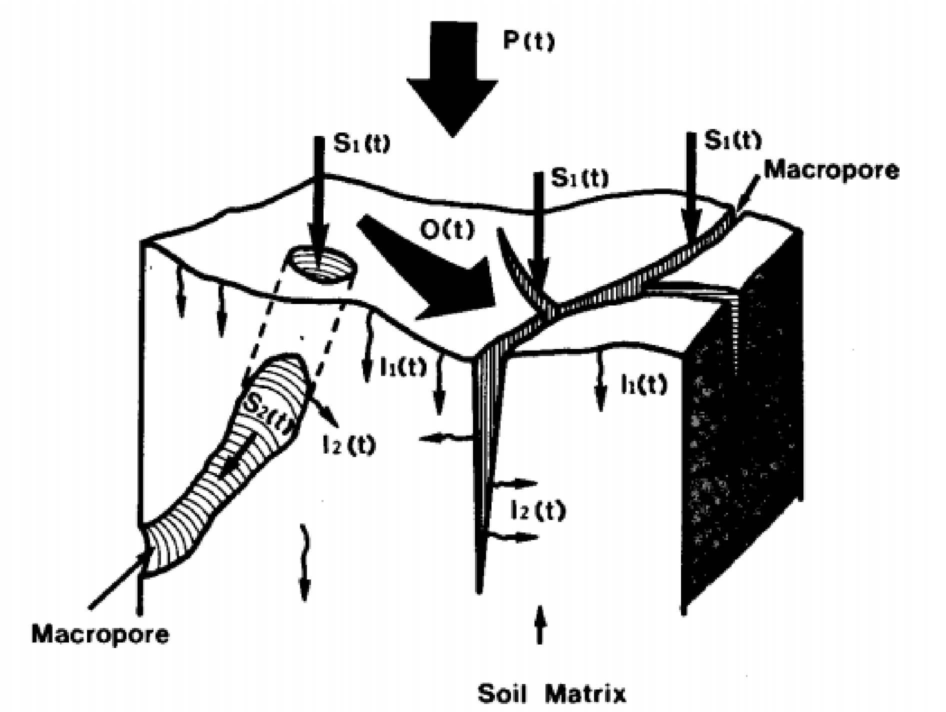


FIGURE 3. DEFINITION DIAGRAM FOR WATER FLOWS DURING INFILTRATION INTO A BLOCK OF SOIL WITH MACROPORES. P(T), OVERALL INPUT (PRECIPITATION, IRRIGATION); I1(T), INFILTRATION INTO THE MATRIX FROM THE SURFACE; I2(T), INFILTRATION INTO THE MATRIX FROM THR WALLS OF MACROPORES; S1(T), SEEPAGE INTO THE MACROPORES; O(T), OVERLAND FLOW (AFTER GERMANN, 1980)

Forest soils present a large number of tubular macropores, especially in the surface layers, because of the high density of live or decayed roots and soil fauna activity. They are very effective in channelling water through the soil, even though unsaturated soil. Cracks and fissures are macropores formed by shrinkage resulting from desiccation of clay soils or by chemical weathering of bedrock material. Natural soil pipes may also be formed because of the erosive action of subsurface flow.
Such macropores allow the vertical by-passing of the unsaturated matrix and allow preferential flow to reach the saturated zone more quickly than through the unsaturated soil matrix (Bouma and Dekker, 1978; Beven and Germann,1982; Germann, 1990).

At the beginning of a rainfall event, all water arriving at the soil surface is absorbed by the micropores of the soil matrix. If rainfall intensity exceeds the infiltration capacity of the matrix, overland flow on small scale will take place. Both macropores and micropores of the soil surface will take up water simultaneously. As soon as there is a significant flow into the macropores, flow down the walls of the macropores will start and lateral infiltration into the matrix will be initiated, and will reduce, temporary, the water flow in the macropore and the depth of water penetration in the soil. The surface flow in the

macropore can greatly increase the surface area available for infiltration into the soil matrix.
If rainfall intensity become higher than infiltration capacity of soil surface (matrix and macropores), then significant amount of water will begin to be stored at the soil surface and overland flow will start on a large scale and free water will start to flow by gravitation within the macropores. Initiation and maintenance of flows in macropores system requires a supply of water exceeding all losses to the matrix.
During a rainfall event this will most commonly occur at the soil surface, when the infiltration capacity of the matrix is exceeded. Nevertheless, not all macropores are connected directly to the surface. In this case the initiation of macropore flow, implies a positive pressure in the soil matrix above a wetting front, that will serve to supply water to the macropores by mean of subsurface interaction (Beven and Germann, 1982).

The preferential flow associated with macropores can then occur in different forms and under different conditions of antecedent wetness and downward movement of free water can be at least partially independent of hydraulic conditions in the smaller pores (Bouma and Dekker, 1978; Beven and Germann, 1982).

The flow of water through the macropores allows important volumes of water to take a preferential path in relation to the rest of the system, thus triggering a smaller response time than through the matrix of the soil, rapidly interconnecting the various layers of the soil (Ambroise, 1998; Beven and Germann, 1982).

1.2.3.3. The piston effect

There is a large agreement on the importance of different subsurface flow mechanism in humid and forested regions. There is a strong evidence for rapid flow via preferred pathways in many forested areas, nevertheless field evidences for macropores flows are sparse and tracer studies have indicated that water store from previous rainfalls dominates the streamflow response to storm rainfall. Old water already stored in the soil matrix may be displaced by the infiltrating rainfall (Pearce, 1986).
This mechanism, called "the piston effect", assumes that rainwater that falls on a slope is transmitted downstream with a pressure wave and causes a sudden exfiltration of old water at the base of the slope. This principle can be explained by analogy with a saturated soil column to which known quantity of water is added. Due to the gravitation effect water moves to the bottom of the column. The piston effect is limited by the fact that the discharge of a certain amount of water only causes equivalent exfiltration if the soil is saturated.

1.2.3.4. The return runoff

The return flow is the subsurface water that during a rainfall event exfiltrates to the surface and adds to overland flow. Return flow occurs when soil capacity to transmit subsurface flow is exceeded, for example in area of discontinuity in the soil type and depth, where lateral subsurface flow may re-emerge to the soil surface.

In practice, for soil saturation conditions, it is difficult to distinguish the saturation overland flow from the return flow, return flow is therefor considered part of the overland flow by Dunne and Black (1970). The overland flow due to soil saturation conditions is a mixture of return flow and overland flow produced by non-infiltrating rainfall. This contribution of old water will then increase the total volume of overland flow.

Dunne and Black (1970), showed that significant amount of stormflow was produced on the hillslope by return flow on saturated area that developed over a small portion of the hillslope where the water table reach the ground surface. Although the return flow had the same origin as the flow that remained below the soil surface, its emergence caused it to have new features. The first is its greater velocity than the velocity of subsurface flow allowing more water to travel from a larger contributing area than for subsurface flow. The second feature is its greater sensitivity to fluctuation of rainfall intensity, which could be accounted for by the short distance of flow beneath the soil. At the end of the rainfall, water drained from the surface and upper few centimeters of the soil within minutes and the rate of overland flow reduced drastically, nevertheless return flow component can in some cases operate in slope-base location for days after storm (Dunne, 1970).

1.2.3.5. Groundwater ridging

Along a perimeter of transient and perennial discharge area, the water table and its associated capillary fringe lie very close to the ground surface. After a rainfall event begins, infiltrating water readily converts the near-surface tension-saturated capillary fringe into a pressure-saturated zone or ground water ridge (Ragan, 1968). This ground water ridge provides the early increase impetus for the displacement of groundwater already in a discharge position, but also results in an increase in the size of the groundwater discharge area, which is essential in producing large contribution to the stream (Sklash and Farvolden, 1979).

The groundwater may discharge directly into the stream through the stream bed or may issue from growing near stream area and flow as overland flow to the stream as in the variable source area –overland flow theory.

1.2.3.6. Storm runoff generation mechanism – brief summary (Slash, 1979)

In order to summarize briefly the Storm runoff generation mechanisms, the Freeze (1974) approach is presented in conclusion.

Partial Area – Overland flow

This concept suggests that runoff water is produced mainly from certain fixed portions of the watershed (usually controlled by soil characteristics) where the soil becomes saturated from above by infiltrating water. After surface detention requirements have been satisfied, the excess water runs off rapidly to the stream as overland flow.

Variable Source area – Overland flow

This concept suggests that runoff is generated from watershed areas (usually controlled by topography, geology and soil type), which have become saturated from below by a rising water table. The source areas, generally located near the stream, may expand and contrast in response to climatic factors. The runoff from the variable source area, consisting of both rain and return flow, runs off to the stream rapidly as overland flow.

Variable Source area – Subsurface storm flow

This concept state that the area contributing to storm runoff expand and contract in response to climatic factors. Unlike the Variable Source Area – Overland Flow theory, the transfer of water from the hillside to the stream is accomplished through subsurface routes. An expanding channel network and translatory flow (displacement or bumping of subsurface water toward the stream) allows the runoff water to reach the stream quickly. The subsurface storm flow may be either saturated-unsaturated Darcian flow through the porous soil matrix or turbulent flow through roots channels, animals burrows and soilcracks or in areas with organized pipe networks as pipeflow.

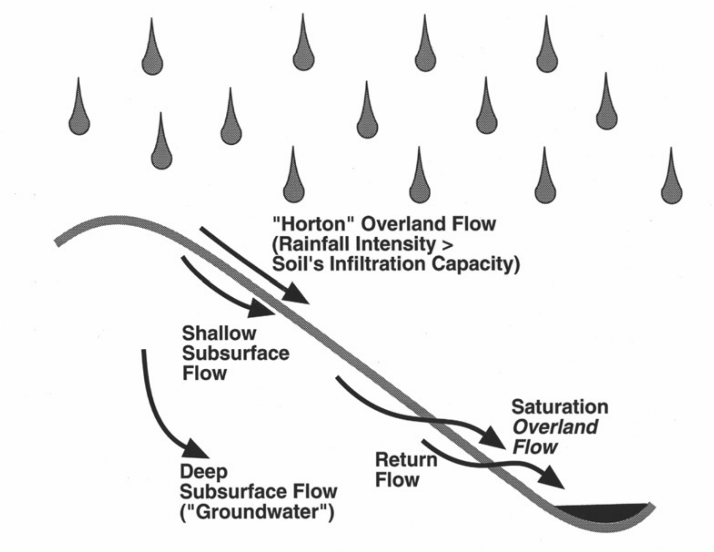


FIGURE 4. *MAIN FOUR DISTINCT RUNOFF PROCESSES (FROM KIRKBY, 2002)*

1.3 Infiltration concept

Besides the concept of runoff, there is another concept that is also fundamental, in the field of the study of hydrological processes and fundamental for water resource management, which is the concept of infiltration.

The infiltration term refers to the vertical transfer of water through the surface layers of the soil, when it is exposed to a rainfall event. The water will first fill the interstices at soil surface and then penetrate to the soil by the action of gravity and the suction forces due to the capillary phenomenon in the soil pores (matrix potential). In the case of precipitation on dry soil, the capillary force predominates at the beginning because the difference in water pressure is very important between the surface and the first centimeters of soil. Then as the soil becomes wetter, this force decreases, and gravity becomes predominant. The action of gravitational forces always exists, but the action of matrix potential disappears for saturated soils.

The infiltration depends in particular on the texture and the structure of the soil. For example, the presence of macropores can alter the hydraulic conductivity of a soil by several orders of magnitude even though they represent only a small portion of soil porosity (Beven and Germann, 1982).

1.3.1. Definitions

To better understand the processes of infiltration, it is necessary to define the following expressions:

Water potential

The term "water potential" describes and predicts water transfers in the soil. Total soil water potential is defined as the amount of work per unit quantity of pure water that must be done by external forces to transfer reversibly and isothermally an infinitesimal amount of water from the standard state to the soil at the point under consideration. At equilibrium, the total potential of water is identical in every point of space. Any variation in the water potential space will cause a spontaneous displacement of water in the direction of decreasing potentials (by convention).

This total soil water potential can be divided in two basic components: gravity and pressure, the latter being decomposable into matrix and hydrostatic components.

Gravitational potential

The gravitational potential, hg, of water is the work required to reversibly move a unit of water quantity from the reference state to the altitude of the point considered in the soil. The gravitational potential corresponds to a displacement in the gravitational field. The reference altitude being the soil surface, the gravitational potential will be negative in the soil, positive above the soil surface.

Pressure potential

The pressure potential, hp, of the water is the work necessary to reversibly move a unit of water quantity from the reference state to the water pressure in the soil volume under consideration. The pressure potential is directly measurable using a tensiometer.

The state of pressure of the water in the soil can be very different depending of soil moisture content. This observation leads to the distinction between two types of pressure potential, hydrostatic pressure potential and capillary pressure potential, one taking over from the other depending on the state of soil saturation.

Hydrostatic pressure potential

When the soil is saturated, the water is subjected to the pressure exerted by the water column which surmounts it at the point considered. The pressure potential is then positive (pressure higher than the reference atmospheric pressure) and corresponds to the height of the water column (m).

Capillary pressure potential or matrix potential

When the soil is not saturated, there are surface tension forces at the interfaces between the gaseous, liquid and solid phases. The capillary pressure potential of the water or matrix potential is linked to the characteristics of the soil that is considered as a porous matrix and related to the pore radius. Capillary pressure is higher for soil with smaller pore radius. The capillary pressure potential in an unsaturated soil is always negative, the pressure of the water in the capillary being lower than the reference atmospheric pressure.

The infiltration rate designates the velocity at which water enters into the soil. It is expressed in mm / h.

The infiltration capacity is the maximum rate at which water can be absorbed by a given soil per unit area under given conditions. If the rainfall intensity is lower than infiltration capacity, then the infiltration rate will be equal to the rainfall intensity. If the rainfall intensity is higher than infiltration capacity, then the infiltration rate will be equal to the infiltration capacity, and the “excess rainfall” (rainfall rate - infiltration rate) will runoff at the soil surface.

Infiltration capacity depends of soil moisture content, and will decrease during storm event with soil saturation.

Hydraulic conductivity is a physical property that measures the ability of the soil to transmit water through pore spaces and fractures in the presence of an applied hydraulic gradient. This ratio depends of the characteristics of the porous matrix (granulometry, particle shape, pore distribution and shape, intergranular porosity), the flow properties (viscosity, specific gravity) and the saturation of the porous matrix. It is expressed as a function of the intrinsic properties of the porous matrix and the fluid.

$$K = \frac{k.\rho.g}{\mu}$$

k: intrinsic permeability of the porous medium (m^2).
ρ: density of the fluid ($kg\ m^{-3}$).
g: acceleration of gravity ($m\ s^{-1}$).
μ: dynamic viscosity of the fluid ($Pa\ s^{-1}$)

Hydraulic conductivity is a decreasing function of the saturation rate of soil (or matrix potential). When soil is saturated, this property is called hydraulic saturation conductivity, Ksat.
Saturated hydraulic conductivity Ks is an essential parameter of infiltration. It represents the limit value of the infiltration rate for a saturated and homogeneous soil.

1.3.2. Factors that influence infiltration

1.3.2.1. The soil type

Soil matrix characteristics such as structure, texture and porosity influence the soil capillarity and absorption forces that influence directly the infiltration rate.
Soil porosity is influenced by the size, the shape, the mineral origin and the organization of the soil particles. Soils with larger pores, such as sandy soils or soils with silt-clay complexes presenting stable aggregates and organic matter, generally offer better conditions for water infiltration.

1.3.2.2. The initial soil moisture content

The initial soil moisture content is an essential factor of infiltration because suction forces are a function of the soil moisture content. When a soil presents low moisture content, the matrix potential is weak, and thus the suction forces are high (due to a strong potential difference between the surface water and the water in the soil) and the infiltration rate is elevated. As soil moisture content increases, the potential matrix energy increases, and the suction forces decrease (due to the decrease in potential difference) which leads to a decrease in infiltration rate.
The Green and Ampt equation (1911) expresses this influence by the depth of the infiltration front, which is inversely proportional to the difference between the initial and final water content.
At the level of overland flow initiation, antecedent water content plays an important role in the time of appearance, since the saturation of the surface takes longer when the soil since is dry. It also influences overland flow rise time, since a steady state is reached faster when capillary forces are low (ie, high saturation).

1.3.2.3. Compacting of the soil surface.

Topsoil compaction is a crucial direct effect of forest harvesting carried out using heavy ground-based logging equipment (McNabb et al., 2001). Compaction can occur also led to tractors and overgrazing in agricultural areaas.

Soil compaction reduces total porosity, pore-size distribution and connectivity, which in turn will change some soil properties like permeability, water retention, shear and penetration resistance.

These changes imply lower water infiltration and hydraulic conductivity, which contributes to increased waterlogging on flat terrain or overland flow and erosion on slopes, especially when confined in ruts (Jansson and Johansson, 1998; Grace et al., 2006).

Susceptibility of soils to compaction varies with soil water content, soil texture and structure, soil organic content. An increase in soil water content implies a higher susceptibility of soils to compaction. (McNabb et al., 2001; McDonald and Seixas, 1997; Han et al., 2006). Nevertheless, soil susceptibility to compaction increases up to a critical moisture content, then it becomes less sensitive to compaction (Hillel, 1998). Generally, the lower the bulk density of the soil, the more prone it is to compaction (Hillel, 1998; Williamson and Neilsen, 2000). Soil texture is also an important factor in compaction susceptibility. Fine-textured soils are generally more susceptible to compaction than coarse-textured ones (Wästerlund, 1985; Hillel, 1998; McNabb et al., 2001; Magagnotti et al., 2012). Increase in soil organic matter content may reduce compactatibilty of soil by increasing resistance to deformation and elasticity of soil (Soane, 1990). Slope gradient also influences compaction severity. It increases with increasing slope angle because of more confined distribution of loads on the ground. Agherkakli et al. (2010) The effect of forest traffic on soil bulk density declines with increasing soil depth (Koolen et al., 1992), but usually occurs in the first few machine passes, while later soil density increases little (Han et al., 2006; Wang, 1997; Wallbrink et al., 2002).

1.3.2.4. The surface crusting

In semi-arid regions and some agricultural areas in any climatic environment, characterized by weak and disperse vegetation cover and high rainfall intensities, soil crusting is a common phenomenon generally attributed to raindrop impact.

The crusting mechanism involves two main complementary processes: (1) physical action including disintegration of soil aggregates and soil particles compaction caused by raindrops, and (2) physical-chemical action included dispersion of aggregates, movement of soil particles and exchange of cations that clog the conducting pores and form a less permeable layer in the topsoil. The formation of seal and crust depend on many factors, including the texture and stability of soil, and crucially the percentage of bare area of the soil surface (absence of litter and vegetation), intensity and energy of rainfall, gradients and length of slope, and electrolyte concentration of the soil solution and rain water. Sealing formation and crust can significantly reduce the infiltration of soil, and increase runoff at surface of soil (Tang et al., 2002).

1.3.2.5. The ground cover.

There is a general agreement that within semiarid areas, sparse vegetation and related microtopography have an important effect on runoff at fine spatial scales (Yair and Lavee, 1976; Scoging, 1982; Wilcox et al., 1988; Dunne et al., 1991). One of these effects is the increased infiltration near and within vegetation cover, which reduces overland flow.

Higher infiltration rates near semiarid vegetation have been attributed to soil properties under plants such as, a lower bulk density (Belsky et al., 1993), a higher soil aggregate stability (Blackburn, 1975) and a higher density of macropores (Dunne et al., 1991, Bergkamp et al., 1996).

Vegetation enhanced infiltration and reduced surface runoff and erosion, and their variability decreased as vegetation cover increases (Cerdà, 1999). However, this relationship can vary greatly depending on the plant architecture (Quinton et al., 1997), stage of plant development, the adaptation of canopy density to available water resources and the stage of succession, especially after land abandonment (Cammeraat et al., 2005).

Plant canopy and litter layer modify the volume and the intensity of rainfall reaching the soil surface and then affect the amount and threshold of overland flow. They reduce the velocity of water runoff at the soil surface and increase the opportunity of water to infiltrate into the soil. Vegetation and litter layer increase the roughness of the soil and thus increase the height of the water, which decreases the overland flow rate (Dunne et al., 1991).

Root systems of the plants also improve soil permeability through the formation of macropores, also strongly increases the conductivity of the soil and thus decreases overland flow (Beven and Germann, 1982). In addition, the vegetation canopy (if close to the soil) protects the soil from rainfall and thus reduces soil compaction increasing indirectly soil infiltration.

Between the vegetation, the soil shows a variable presence of rock fragment cover. The effects of the rock fragment cover were analysed by examining the percentage of cover, the size and the relative position of rock fragments (on top of the soil or partially embedded) (Poesen et al., 1990; Lavee and Poesen, 1991; Poesen and Ingelmo-Sanchez, 1992, Figueiredo and Poesen 1998) and significant changes in the runoff response were found.

The size of rock fragments was the most important factor, followed by rock fragments position (embedded or resting on top of soil surface). Size of rock fragments positively affected splash, wash and runoff and, on the contrary, negatively affected infiltration. Runoff production is lowest for the smallest rock fragments and its velocity is less than that for medium size rock fragments, because of the tortuosity of flow paths, which leads to an increased overland flow discontinuity (Lavee and Poesen, 1991).

A relevant factor determined by Figueiredo and Poesen (1998) was the percentage of rock fragment cover. Total infiltration depth followed a positive relationship with rock fragment cover when rock fragments rested on top of the soil surface. Poesen (1992) discussed the relationship between runoff depth and rock cover. He explained that when rock fragments rest on top of the soil surface, part of the rock flow and part of the Hortonian overland flow generated in the sealed bare soil area between rock fragments, can be absorbed by the unsealed soil surface below rock fragments. The increase of rock cover directly increases the unsealed surface below rock fragments, thus, allowing an increase in infiltration.

In the case of embedded rock fragments, the total runoff was higher than for rock fragments placed on top of the soil surface. Poesen and Lavee (1991) explained that interrill areas covered by embedded rock fragments do not limit overland flow, because of the low macroroughness of these surfaces, and that overland flow is actually promoted, due to water flow generated on the impermeable rock fragment surfaces. As for the shape of rock fragments, no significant effect on global results (Figueiredo and Poesen, 1998).

1.3.2.6. Slope angle

The effect of slope on runoff is not clearly determined. Contradictory observations have been made regarding the influence of slope angle on infiltration.

For most authors (Djorovic 1980, Fox et al., 1997, Chaplot and Bissonnais, 2000) infiltration rate has been observed to decrease with slope angle. They attribute this effect to the decrease in surface storage, effective rainfall intensity, overland flow depth and the increase in flow velocity. Fox et al. (1997) observed decreasing infiltration rates with increasing gradient until a critical threshold was reached; thereafter the infiltration rate was steady and independent of slope gradient. More surprising is that in some studies the infiltration rate increased with increasing gradient.

For interrill conditions, these trends have been ascribed to weaker crusting on steeper slopes because raindrops hit the soil at a more acute angle, and thus with less kinetic energy per unit area of surface (Poesen, 1986). Janeau et al. (2003) observed that the steady final infiltration rate increased sharply with increasing slope gradient. In this specific case, the relationship between slope gradient and infiltrability depends on the nature of the soil and must be examined in the light of surface crusting processes. On steep slopes the horizontal component of the kinetic energy is transformed into shear stress, hampering the development of crusts so that water can still infiltrate (references). However, for soils sensitive to surface sealing, Poesen (1984), Bryan and Poesen (1989) and Bradford and Huang (1992) observe a decrease of overland flow with the slope angle that was attribute to surface crust removal by rill incision Fox et al. (1997).
Slope effect remains difficult to predict and seems to be strongly dependent on the conditions on the soil surface.

1.3.2.7. The microtopography

Microtopography plays an important role in overland flow production through friction, surface storage, and spatial distribution of the flow.
Roughness of the soil is generally characterized by a variance of altitudes. An increase in the coefficient of friction will cause the increase of the water height and decrease the flow velocities.
Soil surface storage essentially creates a delay effect on overland flow initiation due to the filling of the depressions (Sneddon and Chapman, 1989, Darboux, 1999). Between two rainfall events, these depressions can empty and then it will be necessary to fill these depressions again before the overland flow reappears for the following rainfall event.

1.3.2.8. Precipitation intensity

For unsaturated soil conditions, it is the intensity of precipitation that conditions the rate of infiltration (until exceeding the capacity of soil infiltration). Rainfall intensity is an important factor influencing infiltration rate. On some soils, infiltration rate is negatively correlated with rainfall intensity because of the development of surface seals. However, on soils which do not form seals, infiltration rate use to increase with rainfall intensity. Higher rainfall intensities generally exceed the saturated hydraulic conductivity of larger proportion of the soil surface and thereby to raise the spatially average hydraulic conductivity. Increasing rainfall intensity increase overland flow rate but also flow depth. It signifies that the sheet flow inundates progressively a larger fraction of the microtopography. As higher portions of the microtopography use more permeable than lower part of the soil surface, the inundation of the higher parts increase the spatially averaged hydraulic conductivity of the soil surface (Dunne et al., 1991).

Rainfall regime also plays an important role on infiltration. Fang et al. (2008) typify rainfall events in 3 regimes, and show that overland flow coefficients induced by rainfall regime with strong rainfall intensity, high frequency, and short duration were the highest, and those induced by rainfall regime with low intensity, long duration, and infrequent occurrence were the lowest.

1.3.2.9. The presence of a hydrophobic layer on the soil surface.

Water repellency is a natural phenomenon in soils that is variable in space and time. It reduces the affinity of soils to water such that they resist to wetting for periods ranging from a few seconds to hours, days or weeks (King, 1981; Doerr and Thomas, 2000).

It is commonly accepted that soil water repellency is caused by organic compounds derived from living or decomposing plants or microorganisms. Non-biological factors such as coarse soil texture or the occurrence of forest fires induce also increased soil hydrophobicity.

Hydrophobicity has been generally considered to be most severe in dry soil and to decline as soil moisture increases until a critical moisture content is reached, above which a soil becomes hydrophilic (Doerr et al., 2000).

The presence of a hydrophobic layer at the soil surface reduces infiltration capacity of soils, enhanced overland flow and accelerated soil erosion, irregular wetting patterns, as well as development of preferential flow (Ferreira et al., 2000).

1.3.2.10. Scale effects

Scale dependency of overland flow coefficients has been observed in a large number of studies, the overland flow coefficient decreasing as size of area increases. (Lal, 1997; Van de Giesen et al., 2000; Wilcox et al., 1997; Yair and Kossovsky, 2002)

The phenomenon is typically explained as a function of spatial variation in infiltration or more specifically with spatial variability of soil physical properties (Yair and Lavee, 1985; Bonell and Williams, 1986; Sivapalan and Wood, 1986; Julien and Moglen, 1990).

Parameters varying spatially are hydraulic conductivity governing infiltration, microtopography, which sets the amount of surface storage before overland flow begins aa well as slope, vegetation or surface roughness, which determine the depth and velocity of overland flow (Van Giesen et al., 2000).

The spatial variability of these parameters means that for larger area, there exists a higher chance of overland flow encountering patches of soil of higher infiltration capacity and this tends to reduce overland flow. For example, an extreme high value of storage capacity in one point will largely reduce overland flow beyond that point, whereas a small area with zero surface storage will increase the amount of surface water being recorded as moving downhill (Van Giesen et al., 2000).

Another source of scale effects, is the temporal variation of surface runoff (Eagleson, 1970). It takes time for water to move from the top to the bottom of a slope and during this time water may infiltrate. The longer the slope, the longer this infiltration opportunity time will be and shorter slopes may therefore give relatively higher overland flow. The importance of this phenomenon depends on slope length with respect to rainfall duration and the speed with which water moves downhill (Van de Giesen et al., 2005).

Dunne et al., (1991) argued that as the length of the overland flow-producing area increases, so does the depth of overland flow. Consequently, in an area with significant microtopography, a greater proportion of the surface will be inundated leading to an increase on infiltration rate.

Overland flow coefficients under natural rainfall are also related to the effect of temporal variations in rainfall intensity. Natural rainfall exhibits considerable temporal variation in intensity and peaks of overland flow produced during parts of the storm (with high rainfall intensity) can infiltrate during other parts of the storm when infiltration exceeded rainfall. The probability of infiltration of theses picks will be greater the farther downslope they travel.

Finally, downhill infiltration of runoff water after the rainfall intensity falls below infiltration capacity also causes reduction of runoff as the slope length is increased (Van de Giesen et al., 2000).

Stomph et al. (2002) found that scale effects on overland flow also occur along homogeneous hillslopes. They conclude that the scale effect is related to the differences in time needed to reach the equilibrium phase in the hydrograph. An extended residence time of overland flow on a hillslope of greater length can explain to a large extent a substantial reduction of runoff per unit length.

1.4. Objectives and thesis structure

A relationship of interdependence exists between the forest and the aquatic ecosystem, and the degradation or scarcity of one factor will disturb profoundly the nature and quality of the other. Forest environmental services are crucial because of the key roles they play in conservation or preservation of soil and water resources (they slow water dispersion and favour infiltration and percolation of rainwater, which recharges soil and underground water storage). However, the exact nature of this relationship between forest and water resources are not widely known and evaluated. An effective knowledge of hydrological cycle in the forest will provide a better understanding of the relationship between water and forest and lead to a more rational and sustainable management of these natural resources.

The overall aim of this study is to further the scientific knowledge of runoff generation in the two predominant forest types of the mountain ranges of north-central Portugal, and, thereby, improve the foundations for modelling their key hydrological functions (in particular flood and erosion control, surface water availability, recharge of aquifers) under present and future climate and land-cover scenarios.

This work will give continuity to a long-term study on hydrological and erosion processes realized in the ambit of various projects of investigation as well as Master and Phd theses in the western part of the Iberian Peninsula, in the foothills of the Caramulo Mountains, north-central Portugal. The area is mainly covered by forests, pine plantations and eucalyptus plantations which constitute a mosaic of stands in different rotation cycles. Pine plantations reach maturity in about 25-30 years and were gradually supplanted after more or less extend successive forest fires by eucalypt plantations. Currently the prevalent eucalypt species is *Eucalyptus globulus Labill*, which is a fast growing tree species that re-sprouts vigorously from multiple stems after logging. In the region, Eucalyptus plantation typically involves three rotation cycles of 10-15 years, after which a new plantation is established, in general following the removal of the existing root systems and ground operations such as rip-ploughing and bench terracing. The climate of the study area is temperate with wet winters and dry summers, mean annual temperature is 13º while mean annual precipitation varies between 1200 and 1400mm (Agencia Portuguesa do Ambiente, 2011).

The monitoring of the study area started under the IBERLIM project (EV5V-0041) “Land management practice and erosion limitation in contrasting wildfire and gullied locations in the Iberian Peninsula” (1992-1994), in which the impacts of forest fires were assessed. The PhD Thesis of Antonio Ferreira ‘Processos hidrológicos e hidroquímicos em povoamentos de Eucalyptus globulus Labill. e Pinus pinaster Aiton’ assessed the hydrological and hydrochemical processes in the same study area. Some years later the project SILVAQUA (POCTI/MGS/49210/2002) ‘Avaliação dos impactes das alterações climáticas sobre os recursos hídricos e a fixação de CO_2 por povoamentos florestais de crescimento rápido em Portugal’. (2003 – 2007) investigated climatic change impacts on water resources and CO_2 fixation in fast growing forest stands in Portugal. The project HIDRIA – Projecto (PTDC/CTE-GEX/71651/2006) “A multi-stage approach for addressing input data uncertainties in process-based rainfall-runoff modelling for small forested catchments upstream of the Ria de Aveiro” aimed to advance event-based hydrological modelling in small forested catchments, with LISEM and MEFIDIS being used as reference models. The Masters Thesis of Anne-Karine Boulet “Escoamento Superficial nos Eucaliptais da Serra do Caramulo” was also based in the Caramulo mountains.

The specific scientific objectives proposed here are as follows:
i) to analyse temporal patterns in overland flow generation in one Maritime Pine and two contrasting Eucalypt stands, using 1- to 2-weekly runoff data from 16 m^2 plots that have been collected since 1992 for pine plantation and since 2003 for eucalypt plantations and relate them to rainfall regime;

ii) to refine the analysis under point by (a) studying overland flow generation at greater spatio-temporal resolution and (b) relating it to additional key explanatory variables (in particular, interception, topsoil moisture content and topsoil water repellency) through a paired-plot approach;

iii) to extend the analysis under point by assessing the importance of subsurface flow as opposed to overland flow in runoff generation at the slope scale, and, thereby to contribute directly to the validation of the within-catchment modeling results of the HIDRIA project;

(iv) to relate runoff generation at the plot and slope scales to the hydrological response at the outlet of one of HIDRIA experimental catchments, using the data collected by this study as well as past data.

To address the defined objectives this thesis comprises six chapters. The first and sixth chapters concern the general introduction and final remarks of this thesis, respectively, while the other four are individual research papers, published or submitted or to be submitted to SCI journals. These papers have been organized to address the objectives of this work, thus providing the framework for the rest of this thesis.

Chapter 2 presents a description and analysis of temporal patterns in overland flow production in the context of a complete cycle of production of a eucalyptus plantation (three rotation cycles of 12-15 years following each other) by (i) determining the overall differences between the three subsequent rotations cycles; (ii) analysing the inter-annual patterns of these three rotation cycles; and (iii) analysing the seasonal variation
Chapter 3 aims to determine the influence of forest management practices on overland flow generation and soil moisture pattern by comparing three eucalypt stands in successive rotation cycles. To this end, different methodologies were used to measure overland flow (OLF): Simulated rainfall on 0.28m^2 micro-plot (RSE); Natural rainfall on micro-plot (mp); Natural rainfall on 16m^2 macro-plots (MP).

Chapter 4 compares two small forested headwater catchments dominated by maritime pine and eucalypt plantations. These two experimental basins were compared for six contrasting hydrological years, with the aim of identifying possible relations between hydrological response of the catchments and the existing dominant land use, the amount of precipitation and soil moisture content of surface soil. The differences found in the catchment response prompted an attempt to isolate the hydrological mechanisms that would explain the influence of land cover, precipitation amount and soil moisture content on hydrological behavior of the 2 catchments.

Chapter 5 aims to describe overland flow, subsurface flow and streamflow processes in a catchment dominated by Eucalyptus plantations, and, more specifically, to identify if these processes vary through time in particular, with contrasting antecedent soil moisture conditions.

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Chapter 2

Overland flow generation over three rotation cycles of eucalypt plantation in north-central Portugal.

Overland flow generation over three rotation cycles of eucalypt plantation in north-central Portugal

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Abstract

Currently forests occupy 35 % of continental Portugal territory, and more than one quarter of these forests are eucalyptus plantations. This large-scale establishment of eucalypt monoculture plantations has led to concerns over possible hydrological implications, in term of water balance and also storm runoff generation, and this problematic is currently in study at a series of experimental headwater catchments, in the Caramulo Mountains.

The present work focuses on description and analysis of temporal patterns in overland flow production in the context of a complete cycle of production of eucalyptus plantation by (i) determining the overall differences between the three subsequent rotation cycles; (ii) analysing the inter-annual patterns of these three rotation cycles; (iii) analysing the seasonal variation. A monitoring network was installed in 2003 in 3 eucalyptus stands representing the 3 consecutive rotation cycles in eucalypts stands. It included monitoring of overland flow processes and also of 5 parameters (precipitation, soil properties and soil water repellence, vegetation cover and soil moisture content) considered as key factors in the generation of overland flow at plot scale. The main conclusion of this study into annual and monthly patterns of overland flow generation in eucalypt plantations in north-central Portugal and, in particular, the role therein of rotation cycle and, within each cycle, of time-since-the-last-disturbance and rainfall volumes are the following: (i) multi-year and annual overland flow amounts tended to be limited, typically remaining below 10 % of the incident rainfall; (ii) rotation cycle played a marked role in overland flow generation at monthly to (multi-)annual resolutions but this role was more noticeable from the first to the second rotation cycle and from the second to the third cycle; (iii)time-since-disturbance appeared to impact annual and monthly overland flow generation but only during the first rotation cycle and, then, not at all plots and in a dichotomous rather than gradual manner, possibly controlled by some threshold in protective soil cover (vegetation and roots cover); (iv) the runoff response of replicate

plots tended to vary considerably within study sites but these within-site differences did not always have obvious explanations, arguably including because of a lack of ancillary information; (v) annual but especially monthly rainfall totals could explain reasonably well the variation in site- as well as plot-wise overland flow amounts, even if with the exception of several plots.

Keywords
Overland flow; Eucalyptus plantation; Temporal patterns

2.1. Introduction

The establishment of eucalypt plantations throughout the world has exceeded 20.000.000 hectares by 2010. Plantations are mainly located in vast country like Brazil, India and China. Nevertheless, about 3% of the eucalypts of the world are incredibly growing in such a small country as Portugal.

Thus forests occupy 35 % of continental Portugal territory, and more than one quarter of these forest are eucalyptus plantations, nowadays, the dominant tree species in the country. This exotic fast growing tree species introduced in Portugal in the middle of the twentieth century has seen, as in other parts of the world, an effulgent expansion. In fact, eucalypt stands, as the principal raw material for paper pulp production, one of Portugal's leading industries, present a large economic interest. In the Baixo Vouga region of north-central Portugal, boosted by this paper pulp industry, forests occupy half of the territory, of which 2/3 is covered by Eucalypt plantations.

This large-scale establishment of eucalypt monoculture plantations has led to concerns over possible hydrological implications, in term of water balance or also storm runoff generation, and this problematic is currently in study at a series of experimental headwater catchments, in the mountainous part of the Baixo Vouga region.

Overland flow is considered an important hydrological pathway, and frequently cited as the principal stormflow generation process at the origin of the rapid response of the discharge hydrograph. While infiltration-excess OLF is generally associated with (semi-) arid climates (Albergel et al., 2003b) and soils with much lower infiltration capacities than the forest soils in the study region, its potential importance in the streamflow response of the Caramulo headwater catchments cannot be disregarded for various reasons.

First, many Eucalyptus plantations in the study region are intensively managed with frequent use of machinery, leading to significant alterations of the soil surface properties in term of compaction of the topsoil (Gent et al., 1984; Rab, 1994) or low Saturated Hydraulic Conductivity (Ks) (Ziegler et al., 2006). Forest soil may only recover very slowly from soil compaction and subsoil disturbance (Rab, 2004), thus enhancing infiltration-excess OLF production for many years after timber harvesting.

Second, many Eucalyptus plantations in the Caramulo Mountains have a low ground cover of vegetation and litter and a high cover of large stones, especially when they are recently planted. Soil surface conditions play an important role in the regulation of runoff processes (Ruiz Sinoga et al., 2010). Plant cover is one of the main factor determining runoff rate within a given slope (Cerdá, 1998), preventing high runoff rates (Cerdá, 1999; Gomi et al., 2008; Arnau-Rosalen et al., 2008). Sparse floor coverage was described as responsible for the increased overland flow in humid forest (Miyata et al., 2009), and vegetation removal leading to greater total runoff was significantly greater through progressive deterioration of soil physical properties (Castillo et al., 1997).

Lavee and Poesen, (1991) demonstrated that high stone cover tends to induce overland flow, relatively to bare soil, and that overland flow was positively related to stone size. Nevertheless, Cerdá, (2001) established that soil surface rock fragments presence retard surface runoff, and enhance infiltration rates. Poesen et al., (1990) explained the ambivalent effect of stone cover by the rock fragment position, i.e. there is a decrease of the volume of OLF if they rest on the soil surface, but enhance OLF if they are embedded.

Third, the Eucalypt plantations in the study region typically present a strong to extreme soil water repellency, especially after dry periods (Doerr et al., 2000; Keizer et al., 2005a; Leighton-Boyce et al., 2005, Santos et al., 2013), and soil water repellency is widely regarded to reduce infiltration and enhanced overland flow for unsaturated conditions as infiltration-excess OLF (Doerr and Moody, 2004; Ferreira et al., 2000; Keizer et al., 2005b; Leighton-Boyce et al., 2007; Malvar et al., 2013; Mitaya et al., 2009).

As the study region present high annual rainfall amount in the upper Caramulo Mountains in particular, amounting to over 1400 mm per year, and soils tend to be shallow, saturation overland flow processes are expected to play an important role in storm runoff generation in the study region, especially during the wet winter season (Ferreira et al., 2000).

Saturation overland flow production mechanisms are multiple. Saturation overland flow generation is a mechanism commonly associated with the classic Variable-Source-Area (VSA) concept, described by Hewlett and Hibbert in 1967, where the drainage area of a catchment contributing to the storm flow is presented as dynamic. They considered the VSA's as ephemeral extensions expending and contracting in areas adjacent or upstream to the stream channel. Overland flow is produced where upslope subsurface fluxes exceed the capacity of the soil to transmit them, leading to the exfiltration of the water. This theory was supported by the Partial Area Contribution concept described by (Dunne and Black, 1970). Overland flow is produced in a restricted but dynamic area varying seasonally or throughout the storm and situated on saturated zone closed to the stream. Rainfall intensity is described as the main control factor of overland flow production, but fluctuations are also related to topography, soil type, antecedent moisture and rainfall characteristics.

Another approach of the same concept was described as saturation surface resulting from the ground water table rise or perched water table, and its intersection with the soil surface adjacent to the channel, and then the emergence of the water as return flow (Gburek et al., 2006). The return flow can be diffused, but also concentrated in macropores (Germer et al., 2010; Elsenbeer and Lack, 1996).

VSA is not only applicable for areas close to the stream channel. Soils presenting shallow impermeable soil layers (Gburek et al., 2006) or at least marked decrease in Ks down the soil profile (Bonnel and Gilmour, 1978; Cox et al., 1995; Godsey et al., 2004), can developed in case of intense rainfall events, perched water tables and produce a scattered or widespread saturated overland flow over the slope. It is mainly controlled by the topography, microtopography, soil landscape feature, but antecedent soil moisture just influences the volume generated (Elsenbeer et al., 1996).

Some authors presented overland flow processes generated from fixed sources areas. Thus, Betson (1964) deducted mathematically, that only a small part of the watershed will produce overland flow. Other demonstrated that overland flow is generated either on small upland partial areas that are more or less fixed in size and that are controlled by the distribution of soil types (Freeze, 1974).

Nevertheless, it is really important to specify that not all surface saturation areas produced overland flow that reached the stream channel (Srinivasan et al., 2002). Combined by discontinuous nature of overland flow, that can be produce in many places as return flow, it is most difficult to extrapolate plot results to the whole catchment (Elsenbeer and Lack, 1996). These areas with higher proportion to produce overland flow coincide with areas of high topographic convergence and with high values of the λ spatial distribution (Chappell, 2006)

The present work focuses on description and analysis of temporal patterns in overland flow production in the context of a complete cycle of production of eucalyptus plantation by (i) determining the overall differences between the three subsequent rotation cycles; (ii) analysing the inter-annual patterns of these three rotation cycles; (iii) analysing the seasonal variation.

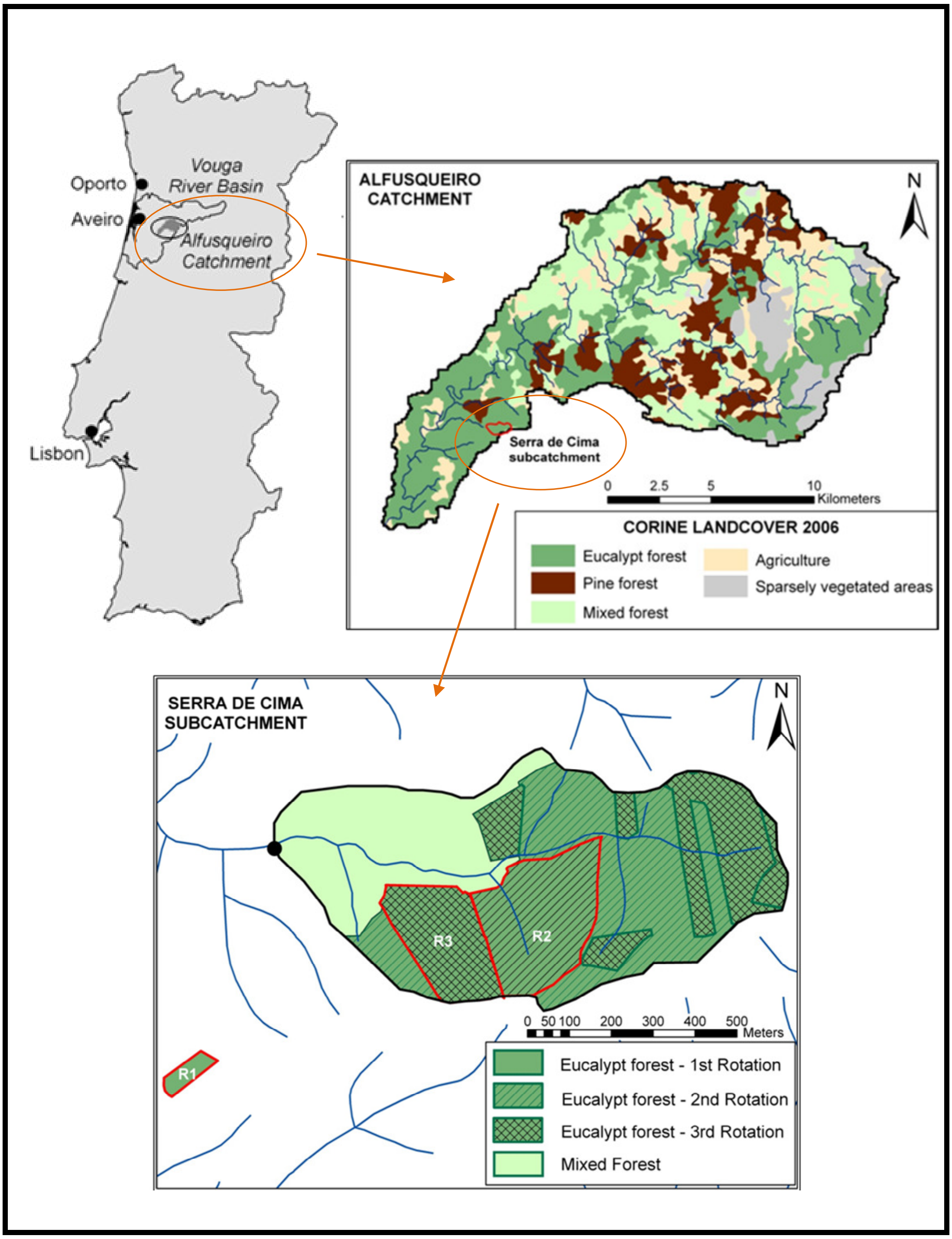
2.2. Materials and Methods

2.2.1. Study area

The present study was carried out in the western part of the Iberian Peninsula, in the foothills of the Caramulo Mountains, north-central Portugal (Figure 1). The area is mainly covered by forests and, in particular, eucalyptus plantations, which now constitute a mosaic of stands in different rotation cycles. The prevalent eucalypt species is *Eucalyptus globulus* Labill, which is a fast-growing tree species that re-sprouts vigorously from multiple stems after logging. In the region, Eucalyptus plantation typically involves three rotation cycles of 12-15 years, after which a new plantation is established, in general following the removal of the existing root systems and ground operations such as rip-ploughing and bench terracing.

The climate of the study area is temperate with wet winters and dry summers, and can be classified as Csb according to the Köppen's system (DRA Centro, 2001). The mean annual temperature is 13°C while mean annual precipitation varies between 1200 and 1400mm (Agencia Portuguesa do Ambiente, 2011).

The Caramulo Mountains are part of the Hesperian Massif, which is dominated by Pre-Ordovician metamorphic sediments of the schist and greywackes complex. Slopes are typically steep (>20 degrees), and soils are stony, weakly-structured and shallow. The soils of the study area are mapped – at a scale of 1:1,000,000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1973).



CHAPTER 2

FIGURE 1. *LOCATION OF STUDY AREA AND STUDY SITE IN THE ALFUSQUEIRO RIVER BASIN, NORTH-CENTRAL PORTUGAL. LAND COVER AND EXPERIMENTAL SET-UP IN SERRA DE CIMA HEADWATER CATCHMENT.*

2.2.2. Study site

This study was carried out in a small, 52 ha headwater catchment of Alfusqueiro River Basin (Figure 1). This experimental catchment “Serra de Cima” is located between 273 and 485 m a.s.l., has steep slopes of, on average, 16°, and is covered for some 70 % by mono-specific plantations of *Eucalyptus globulus* Labill and for the remaining 30 % by a mixed forest of eucalypt, maritime pine and acacias.

A monitoring network of runoff plots was installed in this area to study overland flow processes inside 3 different eucalyptus plantations representatives of the 3 consecutives rotations cycles commonly practiced in the Caramulo Mountain (Figure 2, Table 1). Because of the absence of new plantation inside the "Serra de Cima" catchment, a eucalypt plantation in first rotation was chosen located about 500m outside the catchment boundaries.

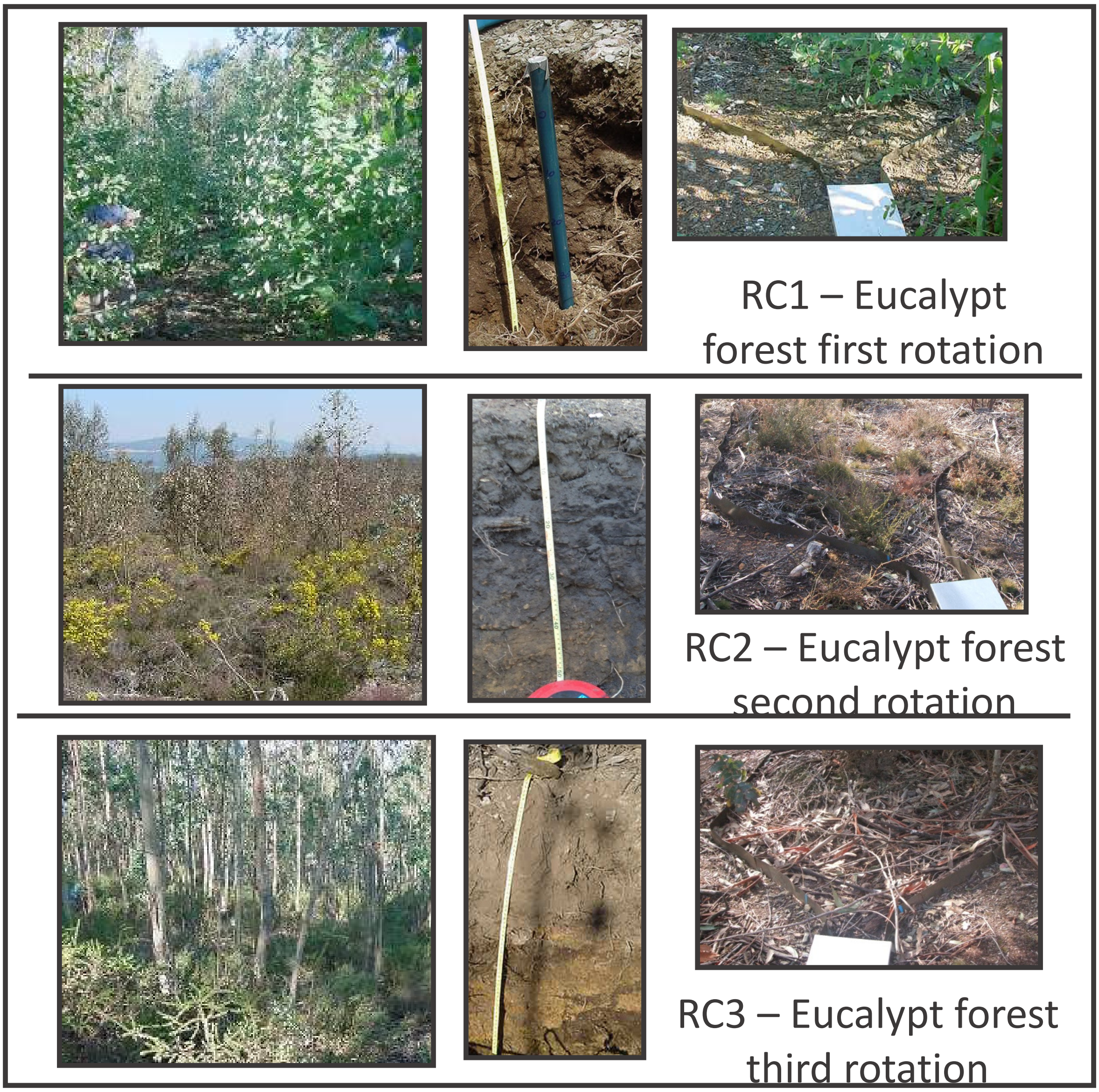


FIGURE. 2. CHARACTERISTICS OF THE 3 EUCALYPT STANDS, GROUND COVER AND SOIL PROFILE IN THE TREE STUDY PLOTS R1, R2 AND R3

TABLE. 1. CHARACTERIZATION OF THE THREE EUCALYPT PLANTATION R1, R2 AND R3

Code	RC1	RC2	RC3
Land use	Eucalypt plantation	Eucalypt plantation	Eucalypt plantation
Rotation	first	second	third
Altitude (m) [1]	410 - 395	475 - 460	475 – 460
Orientação	SO	NN	NN
Slope (degree) [1]	9,0 - 15,0	2,0 - 16,0	9,5 - 18,0
Density (trees/ha)	2604	1371	2437
Litter thickness (cm)	0	3 - 7	5 -10
Understory vegetation (%)	5	57	47
Understory species	*pterospartum tridentatum, erica spp., caluna vulgaris, genista spp., ulex spp.*		
Land-use history			
ploughed and planted	2002	1988	1975
first cut and re-sprouted		2002	1986
second cut and re-sprouted			1998

[1] higher overland flow plot – lower overland flow plot

The 3 plantations are all located at the upper part of a convex-linear hillslopes, with a slope angle that ranged from 3° at the top to 27° at the bottom. The soils of the plantation varied between Humic Regosols on the convergent slope parts and Humic Leptosols on the remaining parts, with soil depths ranging from 20 to 80 cm. The soils are very stony with stone fractions of roughly 50% in the topsoil, probably reflecting past ground operations as rip-ploughing. Soil texture is silt loam, with the silt fraction amounting to roughly 60% and the sand and clay fractions to 20%. The topsoil is rich in organic matter, typically exceeding 10%.

The eucalypt plantation in first rotation cycle (RC1) was logged in spring 2002, rip-ploughed and a new standard plantation of eucalypt was planted with a density of 2500 trees/ha. Understory vegetation and litter layer were very weak at the beginning of the study. The plantation in second rotation cycle (RC2), was rip-ploughed and planted in 1988, logged and naturally re-sprouted in 2003. Re-sprout rate is very low, only 43% of the trunk re-sprouted, which lead to a density of 1057 trees/ha that correspond to 2429 re-sprout/ha. As thinning was made with chainsaw by forest workers, and logged trees were removed manually, soil and understory vegetation were almost undisturbed, dominated by broom (*Pterospartum tridentatum*), heather (*Erica spp.)* and gorse (*Ulex spp.* and *Genista spp.)*. Scrubs covered about 60% of soil with a 40cm mean height, litter layer thickness was very variable but generally between 3 and 7 cm, comprising an F-horizon of Eucalyptus bark, branches and decomposing leaves as well as an O-horizon. The plantation in third rotation (RC3), was rip-ploughed and planted in 1975, logged for the first time in 1986 and then for the second time in 1998, always re-sprouting naturally. Re-sprout was successful; the density was 2437 trees/ha or 3517 re-sprouts/ha. Understory vegetation covered about 50% of the soil and was up to 80cm in height, and litter layer thickness was high, generally about 10cm.

Rainfall at the study site during the study period (2003 ate 2012) present a homogeneous annual precipitation amount distribution with an average similar to the median about 1400mm, -/+ 300mm for Q1 and Q3 and extreme years varying between 870 and 2165mm.

More than half of the annual precipitation fall during wet season from October to January with about 13 rainy days per month and a daily amount about 15mm per rainy day. High daily rainfall amount > 30mm occurred most frequently in October and January (representing normally one or two day per month during these 4 months). Extreme daily amounts > 60mm usually in January, occurred less than 0.5 days per month.

2.2.3. Experimental design

A monitoring network was installed in 2003 in 3 eucalyptus stands representatives of the 3 consecutive rotation cycles (RC1, RC2, RC3) in Portugal. It included monitoring of overland flow processes and also of 5 parameters (precipitation, soil properties and soil water repellence, vegetation cover and soil moisture content) considered as key parameters influencing in the generation of overland flow at plot scale.

Rainfall was measured using a tipping-bucket rainfall gauge with a 0.2 mm resolution (Pronamic RAIN-O-MATIC Professional) linked to an ONSET event data logger that was installed in the Serra de Cima village, at roughly 1 km distance, and 2 storage rainfall gauges that were installed in an open area next to the runoff plots.

Soil properties were assessed for each plantation at soil surface (0-5cm) with a set of 12 samples and down 2 soil profiles of 50cm depth. Soil samples have been analysed at the laboratory in order to determine bulk density, stone percentage, organic matter content and soil water repellence.

A vegetation survey was completed, at each eucalypt plantation, in September/October 2003, inside a fixed vegetation plot of 400m^2. The following parameters were measured: tree density, tree DBH, tree total height, crown surface, crown depth. DBH evolution was monitoring during the study period with a two months interval survey frequency for a sample of 30 trees at each plantation. Annually, was measured the DBH of all the trees from the vegetation plot, in order to confirm the data of sampled trees. A shrub survey was accomplished in June 2004 at each plantation, which included species identification, shrub crow cover (soil projection) and shrub height.

Overland flow measurement was performed weekly, using a set of runoff plots. At each plantation, 3 bounded runoff plots were installed during the summer 2003. The 3 plots are equally distant along the slope from the top to the middle slope and covered various situations of slope angle, ground cover percentage, and micro-topography in order to assess overland generation along the slope.

The plots were 2 m wide by 8 m long, and were bounded by a flexible brass strip of about 20 cm height. The outlet of the runoff plots consisted of a wash trap (with a filter to retain coarse elements) that was connected with a garden hose to diverge the runoff to a tipping-bucket device and, ultimately, collected in 140 L tanks. The tipping-bucket devices consisted of two bascule buckets with a capacity of 0.5 L, whose movement was registered by an analogue counter. The counts of analogue counters were verified at 1 week intervals. During these fieldtrips, also the runoff in the tanks and the rainfall in the storage rainfall gauge were measured.

This system registers the total overland flow amount during the measurement period. The water flow was then lead through a second tube to a 200 L container in order to confirm the water amount indicated by the tipping bucket. In 2007, at each plantation in two of the three plots, analogue counters have been substituted by an ONSET event data logger allowing to measure also rate and timing of overland flow.

Next to each runoff plot, soil moisture profiles were weekly measured with a *Profile Probe type PR1* from the *Delta T Devices* coupled with the *HH2 Moisture Meter* as a portable system. The PR1 consists of a sealed composite rod with 4 electronic sensors (in the form of pairs of stainless steel rings arranged at fixed intervals along its length measuring soil moisture content at 4 different depths within a soil profile (0-10cm, 10-20cm, 20-30cm, 30-40cm depth),

Profile Probes are used in access tubes (28mm diameter) inserted permanently in the soil, which allow rapid insertion and removal and minimizing soil disturbance.

2.2.4. Data collection and analysis

The data set used in this study was collected for almost 12 years, from September 2003 to March 2015. There is a two years gap in the data set, from January 2008 to January 2010, due to lack of human resources and financial funding.

In December of 2009, the plantation R3 was logged and bench-terraced. The collection of data in this plantation was ended at this date.

In December 2012, 2 plots from the plantation R1 were vandalized; not only equipment was damaged, but iron shapes were taken out and soil surface was significantly removed. It was estimated impossible to reinstall the plots properly. Plot 3 escaped the vandals, but for caution the datalogger logger was removed for some months until it was found safe to install it again in September 2013. But a few months later the rest of the equipment was stolen and it was decided to stop monitoring overland flow in this plantation.

Annual OLF rate and amount were calculated for each complete year of records, individually for every plot. Years with incomplete records were not considered. Annual OLF data of the 3 plots installed in each plantation was then processed together in order to obtain an average value of the 3 plots for each plantation. The 3 OLF plots are considered as replicates. But in reality, the 3 plots are installed at 3 different slope positions, with different angles, and these differences could influence deeply the OLF response.
No clear relationship between slope position/angle and OLF production can be discerned from Figure 3. As the slope angle increase from the top to the bottom, similar results are obtained relative to the slope position and slope angle.
Thus four plots produce most elevated annual OLF rate, independently of the slope position/angle, with a tendency to produce more OLF for plots with 2º, 9.5º, 16º and 18º.

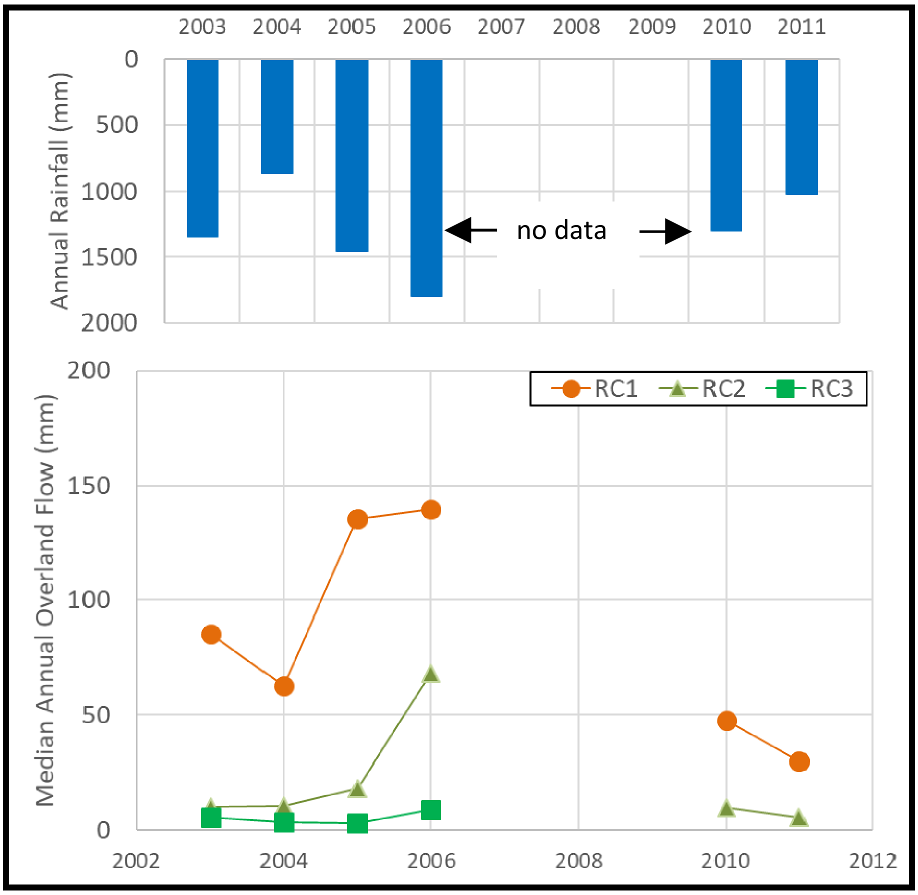


FIGURE 3. ANNUAL RAINFALL (MM) AND SITE-WISE MEDIAN ANNUAL OVERLAND FLOW (MM) FOR THE THREE SUBSEQUENT ROTATION CYCLES (RC1 TO RC3), WITH THE YEAR ON THE X-AXIS REFERRING TO THE START YEAR OF THE HYDROLOGICAL YEAR (I.E. "2003" STANDS FOR THE HYDROLOGICAL YEAR FROM OCTOBER 2003 TO SEPTEMBER 2004)

2.3. Results and discussion

2.3.1. Overall overland flow

The total amounts of overland flow produced by the individual plots over the initial four hydrological years (October 2003 – September 2007) suggested a clear role of rotation cycle. Median values per site decreased markedly from the first (423 mm) to the second (126 mm) and the third cycle (20 mm), corresponding to overall runoff coefficients of 7.8, 2.3 and 0.4 %, respectively. Within-site variation, however, was noticeable and equally seemed related to rotation cycle, as minimum and maximum total runoff amounts differed a factor 24, 5 and 2 for the three subsequent cycles, respectively (26-614, 46-213, 19-39 mm). The particularly large discrepancy among the first-rotation plots reflected the exceptional response of one of the plots (RC1p2), producing 16 and 24 times less overland flow than the other two plots. This exceptional response could not be explained by the plot's slope angle, as that was intermediate (14 vs. 10/18 ^{o}). Probably, it was due to the presence of a depression in the lower half of the plot, enhancing surface storage and, possibly, re-infiltration. In the case of the second-rotation plots, it was not as straightforward to pinpoint which of the plots behaved exceptionally, as minimum and maximum amounts deviated similarly from the median amount (80-90 mm). Slope angle also did not seem to play a key role in explaining the variation among the second-cycle plots, in the sense that the plot with clearly the lowest slope angle (RC2p2: 2 vs. 13/16 ^{o}) produced most overland flow.

The above-mentioned findings were not affected substantially by the results of the two additional hydrological years (October 2010 - September 2012). The median overland flow amounts over this entire 6-year period continued roughly a factor 3 higher for the first than second cycle (501 vs. 160 mm), and the discrepancies between minimum and maximum values were of the same order of magnitude (17 and 4, respectively).

2.3.2 Annual overland flow

2.3.2.1 Among-site differences

The hydrological importance of rotation cycle was also supported by the amounts of overland flow generated over the individual hydrological years (Figure 3). Median site-wise values were consistently higher for the first- than second-rotation cycle during all six years, and for the second- than third-rotation cycle during the four initial years (no data being available for the third rotation afterwards).

Inter-annual variation in site-wise median overland flow amounts was substantial in that minimum and maximum annual figures ranged from a factor of 3 (RC3) and 5 (RC1) to a factor 12 (RC2). In absolute numbers (mm), the differences between site-wise minimum and maximum annual figures decreased markedly with rotation cycle and, thus, with the strength of the overall hydrological response, from 109 (RC1) to 63 (RC2) and 6 mm (RC3).

These differences corresponded to annual runoff coefficients of 2.3-9.3, 0.5-3.8 and 0.2-0.5 %, respectively.

This inter-annual variation in median overland flow amount appeared to be linked to differences in annual rainfall totals, at least at the first and second rotation sites. In both cases, the respective Pearson correlation coefficient (r) was 0.80. At the same time, there was some hint that time-since-last-disturbance played a perceivable role at the first rotation site (i.e. years-since-soil-mobilization) but not at the second rotation site (i.e. years-since-logging). The respective Pearson coefficients were -0.57 and -0.11, respectively. This role of years-since-soil-mobilization was also suggested by the sites median annual runoff coefficients. They were clearly lower during the last two than first four hydrological years (2.9-3.7 vs. 6.4-9.3 %) and were strongly, inversely related with years-since-disturbance (Pearson r of -0.80).

2.3.2.2 Within-site variation

Within-site variation in annual overland flow amounts produced by the three replicate plots at each site was most consistent in the case of the first rotation cycle (Figure 4). Plot RC1p3 produced more overland flow than plot RC1p1 during all six years (10 to 100 % more), while, in turn, RC1p1 produced systematically much more runoff than RCp2 (20-29 times during the initial four years, and 6- 10 times during the last two years). The difference between the first two plots could be related to the considerably greater slope angle of RCp3 than RC1p1 (18 vs. 10 °), possibly overriding the differences in protective ground cover. Both understory and litter cover were higher in RC1p3 than RC1p1, not only in 2004 (40/60 vs. 15/40 %) but also in 2010 (100/100 vs. 40/80 %). As mentioned earlier, the weak runoff response of plot RC1p2 compared to those of RC1p1 and RC1p3, was probably due to the depression in the lower half of the plot. It definitely did not agree with the plot's intermediate slope angle (14 °), or with its comparatively low understory cover or its intermediate litter cover (5/55 % in 2004, and 25/95 % in 2010, respectively). The deviant behaviour of RC1p2 was further evidenced by the poor relation of its annual overland flow amounts with annual rainfall totals over the 6-year period (Pearson r = 0.21), when compared to the other two first-rotation plots (Pearson r = 0.80-0.82).

At the second-rotation site, within-site variation in annual overland flow amounts was consistent in the sense that plot RC2p3 produced more overland flow than plot RCp2 during all six years (1.2 to 6 times) and more than plot RC2p1 during five out of six years (1.4 to 6 times). These differences could be explained by the greater slope angle of plot RC2p3 than of the other two plots (16 vs. 2-13 °). They seemed unrelated to protective soil cover, since understory cover was higher in plot RC2p3 than in the other plots in 2004 (85 vs. 30-35 %) and the same in all plots in 2010 (100 %), and since litter cover was the same in all plots at both occasions (100 %). During the rainiest hydrological year of this study (2006/07: 1796 mm), plot RC2p1 exhibited an exceptionally strong overland flow response. It not only produced almost 3 times more overland flow than plot RC2p3 (188 vs. 68 mm) but also the second highest amount recorded in this study, after the 244 mm produced by plot RC1p3 during that same year. This response was even more surprising given the plot's reduced slope angle of just 2 ^{o}, as opposed to the 10-18 ^{0} of all other second- and first-rotation plots.

At the third-rotation site, the plot-wise differences in annual overland flow were consistent through time in the sense that plot RC3p2 produced the highest amounts during all four years. This suggested that neither slope angle nor protective soil cover played an obvious role in the annual overland response at the third-rotation site. Namely, the RC3p2 plot had an intermediate slope angle when compared with the other two plots (13 vs. 9-15 ^{o}), and, at the same time, the highest understory cover in 2004 (55 vs. 5-13 %) as well as in 2010 (70 vs. 25-50 %), and the same litter cover on both occasions (100 %).

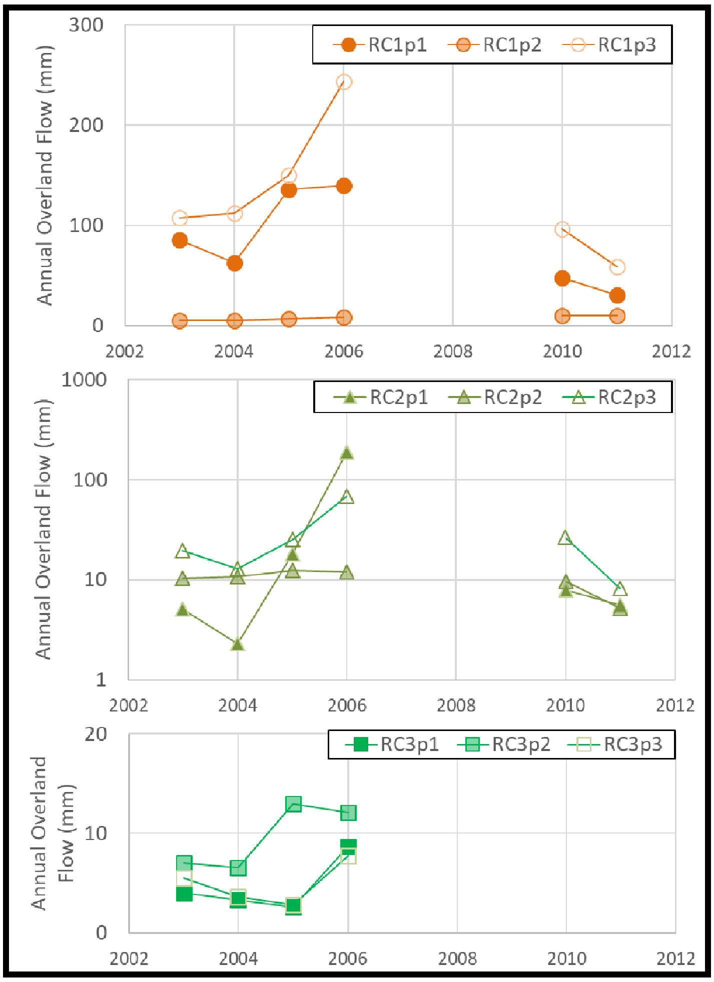


Figure 4. *Annual overland flow (mm) of the individual runoff plots at the three subsequent rotation cycles (RC1 to RC3), with the year on the x-axis referring to the start year of the hydrological year (i.e. "2003" stands for the hydrological year from October 2003 to September 2004). Please note the different y-axis scales.*

2.3.3 Monthly overland flow

2.3.3.1 Between-site differences

The site-wise median monthly overland flow amounts over the initial four study years equally revealed a clearly stronger hydrological response at the first-rotation site than at the second- and third-rotation sites (3.5 vs. 0.5 and 0.4 mm month-1, respectively). The difference between the first- and second-rotation cycle was somewhat smaller over the 6-year period. This was due to a drop in the value at the first-rotation site (to 2.7 mm month-1), as opposed to no change at the second-rotation site. This drop was in line with the suggested role of time-since-soil-mobilization referred earlier.

The role of rotation cycle in site-wise median monthly overland flow amounts was remarkably consistent throughout the study period (Figure 5 and 6). The site-wise median overland flow amounts were higher at the first-rotation site than at the second-rotation site for 63 out of 67 months (excluding the 5 months when median overland flow was zero at both sites). The four months for which the opposite was true, all occurred during the 2006/07 hydrological year. Among these months, December 2006 stood out for a comparatively large difference between the sites (20.6 vs. 0.4-0.9 1mm month-1), while November and especially December 2006 stood out for a relatively strong runoff response at the second-rotation site with, in median, more than 10 and 20 mm month-1, respectively. Possibly, these outstanding runoff amounts at the second-rotation site were related with the high (cumulative) rainfall amounts of not only November and December 2006 but also October 2006, corresponding to the third, fourth and rainiest months of this study (263-355 mm month-1). The monthly runoff response at the first-rotation site even had a stronger tendency to exceed the response at the third-rotation site than that at the second-rotation site. April 2007 was the only exception to this tendency, and one that corresponded to just a minor difference (0.1 mm month-1). In turn, the runoff differences between the second- and third-rotation sites were less consistent at the monthly than annual resolution. Even so, the median overland flow at the second-rotation site exceeded that of the third-rotation site for 29 out of 42 months, while the opposite was true for only four months.

Over the initial four hydrological years, the site-median monthly overland flow amounts were better related to monthly rainfall volumes at the third-rotation site than at the other two sites. The respective Pearson correlation coefficients were 0.84 and 0.61-0.62, respectively. However, if the exceptional runoff amounts of November and December 2006 at the second-rotation site were eliminated from the data set as outliers, the site's Pearson r increased to 0.78. The rainfall-runoff relations over the entire 6-year period were basically the same, with Pearson r's changing at most 0.03. In the case of the first-rotation cycle, not only the rainfall-runoff relation was less well-defined at the monthly than annual resolution, but also the relation of runoff with time-since-soil-mobilization (Pearson r = -0.21). The latter relation was practically inexistent at the second-rotation site as well (Pearson r = -0.08). Also the median monthly runoff coefficients of the first- and second-rotation sites were weakly correlated with months-since-disturbance (Pearson r = -0.27 and -0.08, respectively).

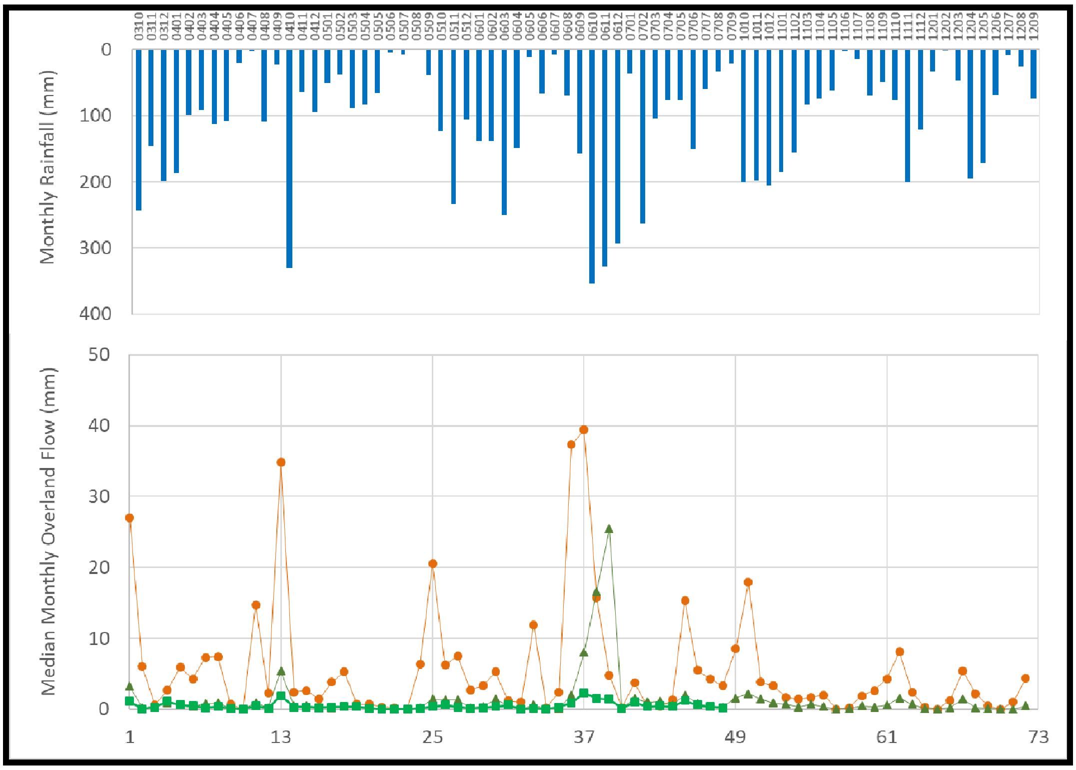


Figure 5. *Monthly rainfall (mm) and median monthly overland flow (mm) at the three subsequent rotation cycles (RC1 to RC3), with the month indicated on the lower x-axis as month since the start of the study, without taking into account the jump between hydrological year 2006/07 and 2010/11, and with the month indicated on the upper x-axes as "YYMM".*

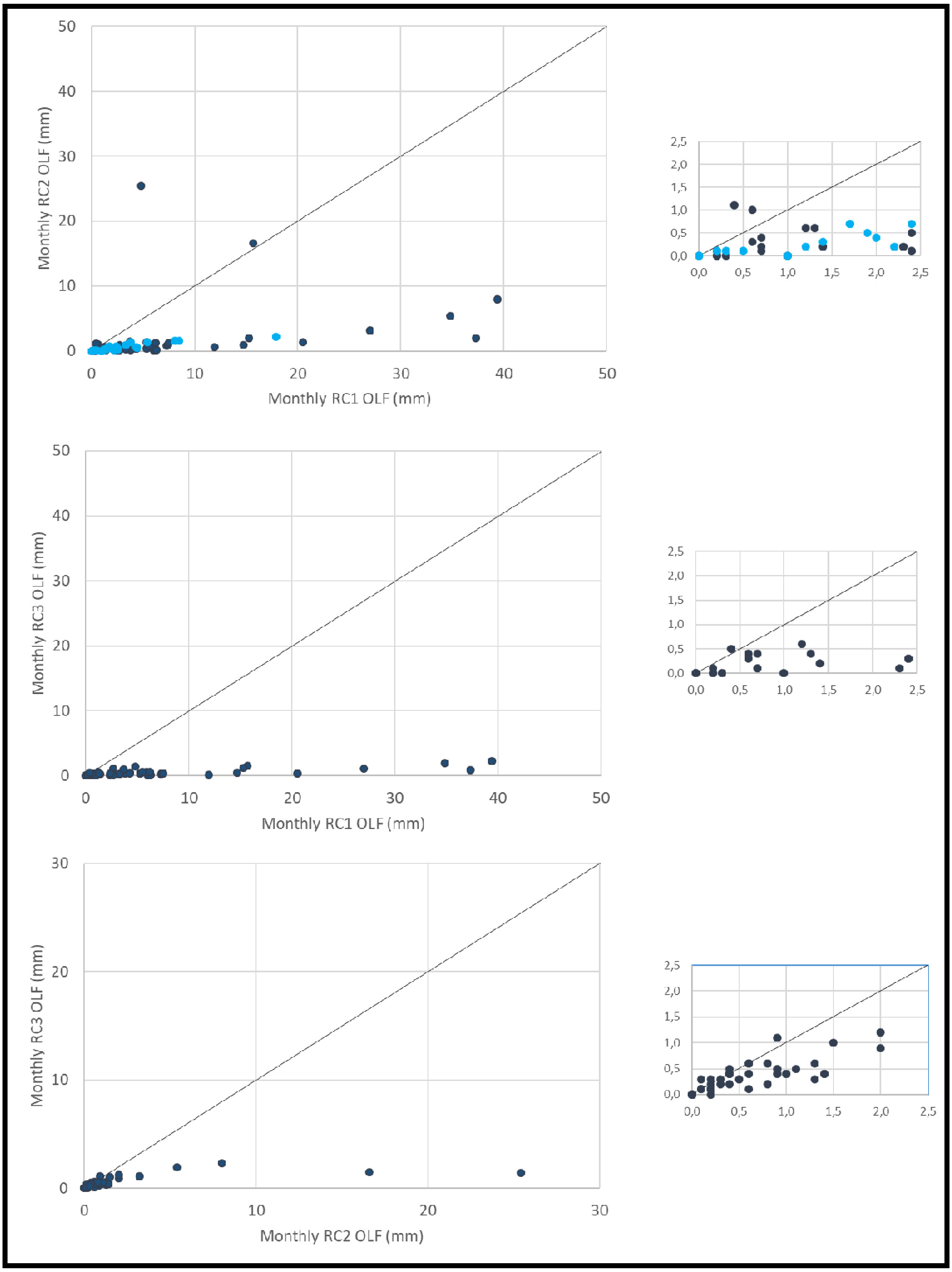


FIGURE 6. *COMPARISON OF THE MEDIAN MONTHLY OVERLAND FLOW AMOUNTS (MM) AT THE THREE SUBSEQUENT ROTATION CYCLES (RC1 TO RC3), I.E. OF RC1 VS RC2, RC1 VS RC3 AND RC2 VS RC3, RESPECTIVELY. THE RIGHT-HAND PLOTS ARE DETAILS OF THE LEFT-HAND PLOTS; THE DARK BLUE SYMBOLS CONCERN THE HYDROLOGICAL YEARS 2003/04-2006/07; THE LIGHT BLUES ONE THE HYDROLOGICAL YEARS 2010/11-2011/12.*

2.3.3.2 Within-site variation

While all three plots at the first-rotation site differed systematically in annual overland flow amounts, they did not in monthly overland flow amounts (Figure 7). Plots RC1p1 and RC1p3 continued to reveal very strong tendencies for stronger runoff responses than plot RCp2 (during 66 and 65 out of the 68 months that produced some runoff, respectively), but did not evidence a clear contrast in monthly runoff response between them. In line with the annual differences, RC1p3 did produce more overland flow than RC1p1 during 36 months, but the opposite was true for 28 months. The discrepancy between the plots' annual and monthly response patterns reflected a marked trend for positive differences between RC1p3 and RC1p1 (RC1p3>RC1p1) to be larger than positive differences between RC1p1 and RC1p3 (i.e. RCp1-RC1p3), as illustrated by the total and average values of the former and latter differences (363.5 vs. 95.2 mm and 10.1 vs. 3.4 mm month-1). In Figure 7, this trend can be grasped from the peaks in overland flow, tending to be noticeably higher in the case of RC1p3 than RC1p1. These peaks in overland flow furthermore seemed to follow a seasonal pattern, typically occurring during the first 1-3 months of the hydrological year (October-December) and often coinciding with peaks in monthly rainfall. Overall, the plots' monthly overland flow amounts could be explained reasonably well by monthly rainfall amounts, even if the Pearson correlation coefficient varied somewhat from 0.60 (RC1p1) to 0.69 (RC1p3) and 0.79 (RC1p2). In the case of the latter plot, there was therefore a major discrepancy between the rainfall-runoff relation at the monthly and annual resolution. Runoff-vs-rainfall plots suggested a weaker response during the last two than initial four hydrological years in the case of plots RC1p1 and RCp3 (Figure 8), but the Pearson r's were (essentially) the same over the initial four year (0.61 and 0.69) as over the full 6-year study period. Furthermore, neither of these two plots revealed a more convincing relation of runoff with months-since-disturbance than the site's median runoff values did, whether in terms of absolute (Pearson r's = -|0.14-0.25|) or relative (Pearson r's = -|0.23-0.26|) runoff amounts. By contrast, the runs-test-above-and-below-the-median did suggest that time-since-soil-mobilization had a noticeable impact on runoff coefficients, at least in the case of plot RC1p1. First, there were significantly fewer runs than expected in the case of a random temporal pattern (number of runs = 23; p ≤ 0.01 and only four of these runs occurred during the last two hydrological years, reflecting a predominance of below-median values (17 out of 24).

Also at the second-rotation site, the differences in runoff response between the three plots were less consistent at the monthly than annual resolution (Figure 7). Plot RC2p3 still produced more overland flow than plot RC2p1 during the majority of months (32 as opposed 23, with 8 ties and 9 months without any overland flow), but not than RC2p2 (22 vs. 35 months). Even more so than at the first-rotation site, these discrepancies between the two temporal resolutions tended to be strongly linked to individual runoff peaks during autumn-early winter, when plot RC2p3 produced an excess overland flow sufficient to compensate for opposite differences during the remaining part of the year. As referred earlier, the hydrological year 2006/07 was an exception in this respect, as plot RC2p1 compensated RC2p3's excess runoff of October by a strong runoff response during November (39.9 mm) and an extreme response during December (122.9 mm). The latter response corresponded to the largest runoff volume recorded in this study as well as to this study's highest runoff coefficient (41.9 %). Even though especially RC2p1's December response was puzzling, also in view of the plot's reduced slope angle (2^o), it was still reasonably comparable in both absolute and relative terms to the second strongest response of this study, with 102.2 mm produced by plot RC1p3 during the same month. Furthermore, the two responses did not contribute markedly to the weak monthly rainfall-runoff relation of plot RC2p1 compared to the site's other two plots (Pearson r = 0.37 vs. 0.65-0.71). Removing either or both months from the computations increased the Pearson r with at most 0.03.

At the third-rotation site, the monthly differences between the three plots agreed reasonably well with their annual differences in the sense that they revealed strong tendencies for plot RC3p2 to produce more overland flow than the other two plots (Figure 7). The runoff response of plot RC3p2 exceeded that of plot RC3p1 for 34 out of 39 months (with 4 ties and 5 months without any runoff), and that of plot RCp3 for 30 out of 41 months (with 2 ties). Similar to what was observed at the other two sites, plot RC3p2 also stood out for revealing the highest runoff peaks during the initial months of the hydrological years, even if these peak values themselves never exceeded 4 mm month-1. Like was the case at the second-rotation site, one of the three plots stood out for a relatively poor rainfall-runoff relation. Pearson r was 0.36 in the case of plot RC3p3 as opposed to 0.80-0.83 in the case of the other two plots. This deviant behaviour of RC3p3's seemed to originate from the 2006/07 hydrological year and, in particular, its initial three months as well as two of its final months (June and September 2007), producing comparatively small and large amounts of overland flow, respectively. Removing these five months from the computations increased RC3p3's Pearson r to 0.73.

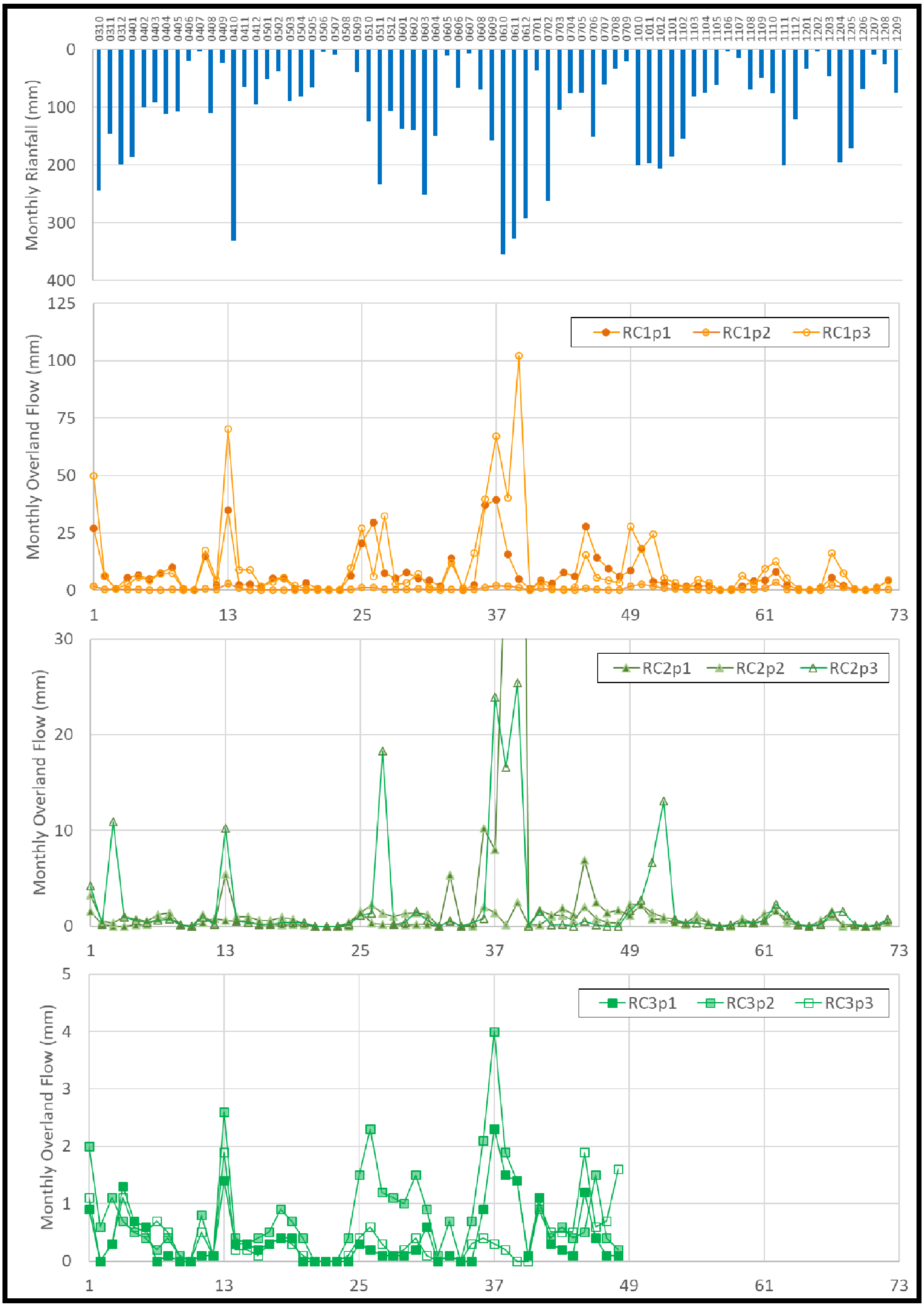


FIGURE. 7. MONTHLY RAINFALL (MM) AND MONTHLY OVERLAND FLOW (MM) PRODUCED BY THE INDIVIDUAL RUNOFF PLOTS (P1 TO P3) AT THE THREE SUBSEQUENT ROTATION CYCLES (RC1 TO RC3). SEE FIGURE 5 FOR EXPLANATION OF THE X-AXIS SCALES.

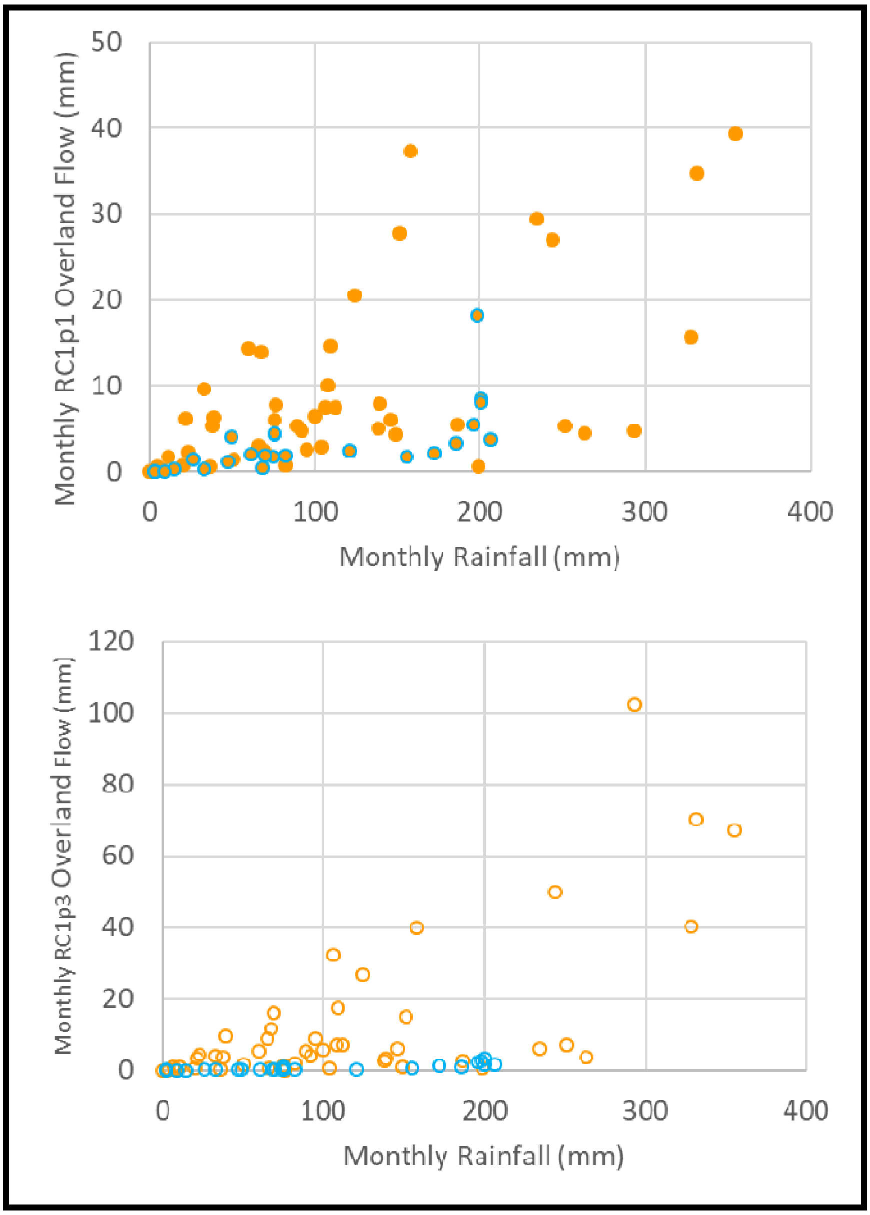


***FIGURE 8.** MONTHLY RAINFALL (MM) VS. MONTHLY OVERLAND FLOW (MM) FOR RUNOFF PLOTS RC1P1 (UP) AND RC1P3 (BELOW), USING DIFFERENT SYMBOLS FOR THE 2003/04-2006/07 (ORANGE OUTLINES) AND 2010/11-2011/12 HYDROLOGICAL YEARS (BLUE OUTLINES).*

2.4. Conclusion

The main conclusion of this study into annual and monthly patterns of overland flow generation in eucalypt plantations in north-central Portugal and, in particular, the role therein of rotation cycle and, within each cycle, of time-since-the-last-disturbance and rainfall volumes are the following:

- multi-year and annual overland flow amounts tended to be limited, typically remaining below 10 % of the incident rainfall;

- rotation cycle played a marked role in overland flow generation at monthly to (multi-)annual resolutions but this role was more noticeable from the first to the second rotation cycle and from the second to the third cycle;
- time-since-disturbance appeared to affect annual and monthly overland flow generation but only during the first rotation cycle and, then, not at all plots and in a dichotomous rather than gradual manner, possibly controlled by some threshold in protective soil cover;
- the runoff response of replicate plots tended to vary considerably within study sites but these within-site differences did not always have obvious explanations, arguably including because of a lack of ancillary information;
- annual but especially monthly rainfall totals could explain reasonably well the variation in site- as well as plot-wise overland flow amounts, even if with the exception of several plots.

2.5. Acknowledgments

The present study was carried out in the framework of the PhD research fellowship of A-K Boulet (SFRH / BD / 91690 / 2012), funded the Foundation for Science and Technology (FCT) of Portugal through the Operational Programme POPH - QREN - Priority Axel 4 - Advanced Training and co-funded by the European Social Fund (ESF) and national funded from the MEC.
It received the support from the HIDRIA project (PTDC/CTE-GEX/71651/2006) also funded by the Foundation for Science and Technology (FCT).

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Chapter 3

Overland flow generation and soil moisture patterns at three eucalypt rotation stages across different methodologies and spatio-temporal scales.

Overland flow generation and soil moisture patterns at three eucalypt rotation stages across different methodologies and spatio-temporal scales.

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Abstract

Currently, eucalypt plantations cover 26% of forest surface in Portugal and became the dominant tree species. The leading role of the eucalypt business in Portuguese economy, especially for paper pulp industry, is clear and eucalyptus area is likely to increase in the future. In this context is of utmost relevance to evaluate eucalypt stands impact on water available and soil quality. This work aims to determine the influence of forest management practices on overland flow generation and soil moisture pattern by comparing three successive eucalypt stands rotations R1, R2 and R3. To this end, different methodologies were used to measure overland flow (OLF): Simulated rainfall on 0.28m^2 micro-plot (RSE); Natural rainfall on micro-plot (mp); Natural rainfall on 16m^2 macro-plots (MP). Results establish (i) Overall OLF values: the three eucalypt stands suffered variation in function of the measurement method adopted. But the R1 plantation always presented higher OLF rates (40% vs 32% and 33% for RSE, 23 % vs 15% and 17% for mp and 7% vs 5% and 1% for MP). (ii) Temporal pattern of OLF: Seasonal OLF rate followed the same temporal trend at mp and MP scale for the 3 three eucalypt stands showing an increase of OLF amount during the wet period and an increase OLF rate during the dry season for R1 and R3 at both scales. (iii) identify key factors in OLF generation: Plot length has the more significant effect on OLF rate, followed by Plantation aging. OLF presented a positive relationship with stone cover and a negative one with litter cover. Soil moisture content is the main factor driving OLF temporal pattern, related with the appearance of SWR during the dry season, and soil saturation during wet season leading to high production of OLF concentrated in some few extreme events.

Key Words

Overland Flow, Eucalypt stand, scale effect, key factors

3.1. Introduction

Currently, forest covers 35% of continental Portugal and the last forest inventory revealed that eucalypt plantations have dethroned the emblematic cork oak tree, becoming the predominant forest species occupying 26% of forest surface. Eucalypt area extended continually accompanying the expansion of paper pulp industry. This fast expansion of eucalypt was due to a combination of factors: (i) the high quality of *E. globulus* wood material as a raw material for pulp (ii) the high productive characteristics of the species (fast growing species) combined with a perfect adaptation to climate and soil in many regions of the country, (iii) the short rotation period as a large economic attractiveness for land owners.

Expansion of eucalypt is not geographically homogeneous, it followed the eco-physiological preferences of the *Eucalypt globulus* species well adapted to temperate and humid climate. Half of the Aveiro district (predominantly in the Coastal part of Portuguese Centro Region) is occupied by forest, of which 70% are eucalypt stands (VI forestry inventory).

Eucalyptus globulus is a fast growing species particularly well adapted to coastal center clima of Portugal. The stands are intensively managed in a short rotations system. The first cycle of planted seedlings (single stem) is followed by 2 coppiced stands, with an average cutting cycle of 12 years (Soares and Tomé, 2001).

The forestry activity sectors accounts for 3% of national business volume and number of employees, half corresponding specifically to the paper and pulp sector. The leading role of the eucalypt business in Portuguese economy is clear and even if this is a controversial subject, especially in what concerns ecological subjects, the eucalyptus area is likely to increase in the future.

In this context it is of utmost relevance to develop sustainable land management and more efficient soil conservation strategies. Integration of economic and environmental interests in a comprehensive manner is needed to achieve sustainable land management objectives. This requires the evaluation of eucalypt stands' impact on water available and soil quality.

Most previous research performed on eucalypt stands focused on post-fire effects (Shakesby et al., 1996, Malvar et al., 2011; 2013), neglecting the long-term behaviour of plantations and leading to a lack of quantifiable information concerning hydrological processes in eucalypt stand especially in terms of overland flow (OLF).

OLF can be quantified by different methods. In fact, we need to determine the most appropriate method as a function of soil conditions and the intended application of the data set (Reynolds et al., 2000). Different methods produce different values for infiltration/OLF rates and presented varied behaviours according to the soil properties. The selection of a technique will influence the measured value (Verbist et al., 2013).

Rainfall simulation experiments on microplots (RSE's) have been used to quantify overland flow in Portuguese eucalypt stands (Coelho et al., 2005; Leighton-Boyce et al., 2007, Malvar et al., 2011; 2013). RSE's allow the repeatability and comparability of the experiments and is extremely time-effective. Nevertheless, rainfall characteristics of RSE's are not representative of natural rainfall and only a few studies such as Malvar et al., (2015) have the opportunity to compare results obtain for the same plots for RSE's and natural rainfall. In addition to rainfall characteristics, OLF generation can also be influenced by scale effects. Most OLF studies opt for the use of microplot easier to install and monitories than macroplots, nevertheless Prats et al. (2012, 2013) found significant differences between OLF rate produced at different plot sizes.

Scale dependency of OLF coefficient is observed in many studies and is generally explained as a function of spatial variation in infiltration attributed to the spatial heterogeneity of soil surface conditions like soil properties and vegetation (Ruiz Sinoga et al., 2010; Smets et al., 2008) or macroporosity (Heeren et al., 2015). The phenomen of connectivity between infiltrating and runoff producing area was also evocated to explain the reduction of OLF coefficients for longer slopes. (Cerdan et al., 2004; Boix-Fayos et al., 2006,2007). Van de Giesen et al., 2011, stated that temporal dynamics of rainfall, rather than spatial variability, is the cause of the observed scale effects. Wainwright and Parsons (2002) suggest an alternative explanation, considering that scale dependency is the combination of temporal variation in rainfall intensity and run-on infiltration.

In a general way, soil and land use spatial patterns play an important role in the magnitude of processes at a given scale and connectivity of water processes influences process response at wider systems (Ferreira et al., 2000, 2008).

This work aims to determine the influence of forest management practices on overland flow generation by comparing three successive eucalypt stands rotation cycles, namely a recently ploughed and planted- first rotation plantation (R1), a young regenerated-second rotation plantation (R2) and a mature regenerated- third rotation plantation (R3). To this end, different methodologies were used to measure overland flow (OLF): (i) simulated rainfall on micro-plot (0.28 m^2); (ii) natural rainfall on micro-plots; and (iii) natural rainfall on macro-plots (16m^2). The specifics objectives are to: (i) establish overall OLF values; (ii) determine the temporal pattern of OLF and; (iii) identify key factors in OLF generation, with special attention on soil moisture dynamics; for each of the 3 rotation cycles and for each methodology.

3.2. Materials and Methods

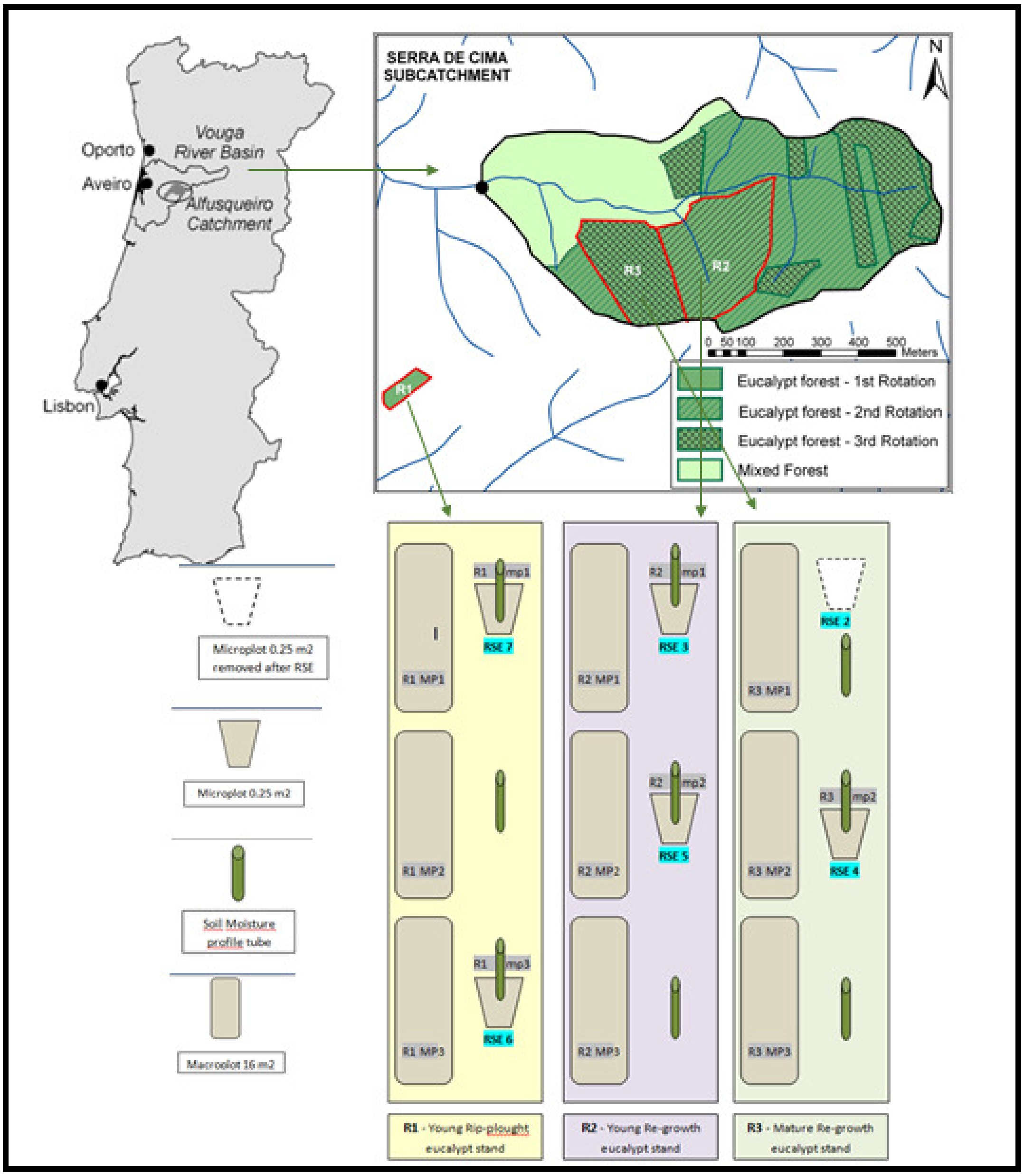
3.2.1. Study area

This study was carried out in the foothills of the Caramulo Mountains, north-central Portuguese littoral mountain range (Figure 1). The area is mainly covered by *Eucalyptus* *globulus* Labill. plantations in different rotation cycles. *Eucalyptus globulus* is a non-native fast-growing tree species capable of regrow from stumps after logging. In Portugal, Eucalyptus plantations management typically involves three harvesting cycles of about 10-12 years. Prior to first planting or after 3 harvesting cycles, ground operations such as deep rip-ploughing or bench terracing are performed and new seedling are planted.

The climate is temperate Mediterranean with wet winters and dry summers, and can be classified as Csb according to the Köppen's system (DRA_Centro, 2001). The mean annual temperature is 13ºC while mean annual precipitation varies between 1200 and 1400mm (Agencia Portuguesa do Ambiente, 2011).

During the reference 12 years period, average annual rainfall amount at the nearest meteorological weather station (Pousadas, 1.5 Km apart from the study area) was 1403 mm. The maximum annual value was 2165mm and the minimum 870mm. The autumn and winter are the wettest seasons; respectively 41% and 31% of the annual rainfall is falling during this period. The summer period is especially dry, only 9% of the annual rainfall occurs during this season.

The Caramulo Mountains are part of the Hesperian Massif, which is dominated by Pre-Ordovician metamorphic schist and greywackes. Slopes are typically very steep (>20 degrees), and soils are stony, weakly-structured and shallow. The soils of the study area are mapped – at a scale of 1:1,000,000 – as a complex of Humic cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1973).



CHAPTER 3

FIGURE 1. *LOCATION OF THE STUDY AREA IN THE VOUGA RIVER BASIN, NORTH-CENTRAL PORTUGAL (LEFT); STUDY SITES IN THE SERRA DA CIMA SUB-CATCHMENT (RIGHT), AND SCHEMATIC REPRESENTATION OF THE OLF-SOIL MOISTURE MONITORING SET-UP IN THE R1, R2 AND R3 SITES (BOTTOM). SITES CODES ACCORDING TO TABLE 1.*

3.2.2. Study sites

This study was carried out at the Serra de Cima subcatchment (52 ha), a small tributary of the Alfusqueiro catchment which drains to the Vouga river basin (Figure 1). Mono-specific plantations of eucalypts cover around 70 % of the Serra de Cima catchment. Three eucalypt plantations in successive harvesting stages (first, second and third rotation R1, R2 and R3) were selected at the upper part of convex-linear hillslopes. The slope angle ranged from 3º at the top up to 27º at the bottom. R1 was contour ploughing planted with eucalypt seedling 4 years earlier, R2 was logged and naturally re-sprouted 3 years earlier, and R3 was logged for the second time and naturally re-sprouted 8 years earlier (Table 1). Understory vegetation is dominated by broom (*Pterospartumtridentatum*), heather (*Erica spp.)* and gorse (*Ulex spp.* and *Genista spp.)*. Vegetation cover is denser and higher at R2 and R3 as logging doesn't disturb significantly understory vegetation.

CHAPTER 3

TABLE 1 – STUDY SITE GENERAL CHARACTERIZATION

Site name		R1				R2				R3			
Main characteristics		Young Rip-ploughed eucalypt stand				Young Re-growth eucalypt stand				Mature Re -growth eucalypt stand			
Rotation cycle	(n)	1st				2nd				3rd			
Years after ploughing	(n)	4				17				34			
Years after re-growth	(n)	4				3				8			
Aspect	(º)	N210E				N350E				N340E			
		n	**mean**	±	sd	*n*	**mean**	±	sd	*n*	**mean**	±	sd
Slope angle	(º)	*6*	**13**	±	5	*5*	**11**	±	5	*5*	**11**	±	5
Vegetation													
Vegetation cover	(%)	*6*	**18**	±	19	*5*	**50**	±	31	*5*	**23**	±	24
Vegetation height	(cm)	*6*	**22**	±	15	*5*	**32**	±	11	*5*	**35**	±	27
Litter													
Litter cover	(%)	*6*	**48**	±	24	*5*	**89**	±	15	*5*	**93**	±	16
Litter depth	(cm)	*6*	**1**	±	0	*5*	**5**	±	2	*5*	**6**	±	3
Water retention	(mm.mm^{-1})	*5*	**0,3**	±	0,1	*3*	**0,4**	±	0,1	*5*	**0,3**	±	0,1
Soil depth	(cm)	*2*	**43**	±	4	*2*	**45**	±	7	*2*	**45**	±	7
Mechanic soil properties													
Penetration resistance	(kg.cm^{-2})	*6*	**3,0**	±	0,1	*5*	**1,2**	±	0,1	*5*	**1,5**	±	0,2
Shear strength	(kg.cm^{-2})	*6*	**3,7**	±	0,7	*5*	**3,0**	±	0,1	*5*	**2,5**	±	0,1

Litter cover and depth at R2 and R3 are similar, about 90% of soil surface is covered by a deep decayed litter layer, about 3-7cm depth for R2 and 5-10cm depth for R3. At R1, the litter layer covers about 50% of the soil surface, is irregular and shallow principally constituted by leaves and bark very partially decayed.

The soils varied between Humic Regosols on the convergent slope parts and Humic Leptosols on the remaining parts, with soil depths ranging from 20 to 80 cm. Soil texture is silt loam, with the silt fraction amounting 60% and the sand and clay fractions to 20% each. The soils are very stony with stone fractions of roughly 50%. The rip-ploughed plantation R1 shows the higher average superficial stones percentage (about 60% vs about 40% for R2 and R3). Topsoil bulk density is also higher in the case of the recently rip-ploughed R1 (1 g.cm^{-3} vs about 0.85 for both R2 and R3). The topsoil is rich in organic matter, typically exceeding 10% and MO content turn lower with increasing soil depth Soil water repellency ranges from weak, on R1 to extremely repellent, on R2 and R3 (0 MED Class versus 5 and 7 for both R2 and R3 (Figure 2).

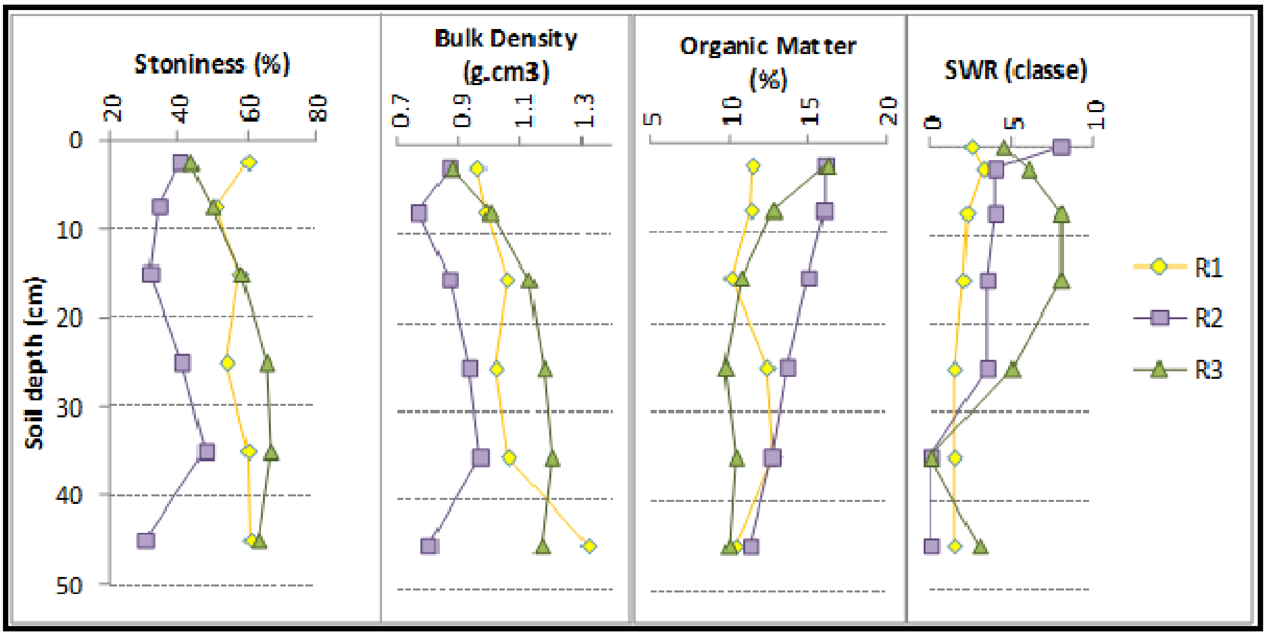


FIGURE 2. MEAN VALUES OF STONINESS (STONE PERCENTAGE BY WEIGHT), BD (BULK DENSITY), OM (ORGANIC MATTER), AND SWR (SOIL WATER REPELLENCE) IN THE TWO SOIL PROFILES IN EACH ONE OF THE THREE STUDY SITES R1, R2, R3. SITES CODES ACCORDING TO TABLE 1.

3.2.3. Experimental design

The experimental set up of overland flow measurements comprised (i) rainfall simulations campaign on microplots (0.28m2), natural rainfall on micro-plots (0.28 m^2), and natural rainfall on macro-plots (16 m^2) installed in the three study sites R1, R2 and R3 (Figure 1).

Rainfall simulations campaign was carried out between 10 May 2006 and 12 July de 2006 over two micro-plots of 0.28m^2 per study site. The micro-plots were squared plots bounded by a rigid stainless steel of 15 cm height and installed along the slope. Rainfall simulations were carried out using a portable rainfall simulator following the design by Cerdà et al. (1997) and with modifications by De Alba (1997). The rainfall simulator provides a rainfall intensity of 46 mm h^{-1} (calibrated in the laboratory) during 2 h totalizing a total rainfall amount of 92 mm per simulation. Soil moisture and overland flow volume were measured every 5 minutes during the 2 h of rainfall simulation and the

start and end OLF times were also registered. Additionally, soil moisture content was measured 24h, 48h and 7 days after the simulation.
Natural rainfall overland flow generation was monitored weekly from 27 September 2006 to 18 October de 2007 at micro-plot ($0.28m^2$) and macro-plot scale ($16m^2$). The same micro-plots used for the rainfall simulations were connected to tanks by hoses and overland flow was measured at weekly intervals. Three macro-plots were installed in each site at equal distances from the top to the middle slope (Figure 1). The macro-plots were 2 m wide by 8 m long bounded by 20 cm wide metal sheets inserted around 5 cm into the soil. OLF was collected at the outlet of each plot and canalized to tipping-bucket equipped with analogue counter checked at 1 week intervals.
Soil moisture at 4 different depths (10-20-30 and 40 cm) was assessed with a Profile Probe type PR1, every 5 minutes during the rainfall simulation experiments and then weekly during the study period for three profile-tubes at each plantation, two of them already installed inside the micro –plot used for RSE's (Figure 1). At each measurement, soil moisture was recorded at 4 different depths (10-20-30-40 cm) and 4 directions (North, South, East, West) with a Profile Probe type PR1 coupled to a portable HH2 Moisture Meter from Delta T Devices. Readings were performed inserting the probe equipped with 4 electronic sensors into access tubes installed permanently into the soil. At each reading, a signal is applied to the rings which transmit an electronic field that penetrated about 10cm into the soil. The default output from PR2 is the measured permittivity. Each sensor gives a voltage output which is converted into soil moisture using the supplied general soil calibrations.
Rainfall was measured using a tipping-bucket rainfall gauge with a 0.2 mm resolution (Pronamic RAIN-O-MATIC Professional) linked to an ONSET event data logger that was installed at roughly 1,5 km distance from the study sites. Two additional cumulative rainfall gauges were installed at the plantation R1 e between R2 and R3.

Soil properties were assessed down two soil profiles at each plantation at 5-6 depths (0-5, 5-10, 10-20, 20-30, 30-40 and 40-50 cm if soil depth allowed it). At each depth, 4 soil samples were collected and analysed in the laboratory to determine stone percentage, bulk density and organic matter content (Botelho da Costa, 2004) (Figure 2). Additionally, soil moisture content and soil water repellency were determined *in situ*. A Profile Probe type ML-2 coupled to a portable HH2 Moisture Meter from Delta T Devices was used to measured soil moisture. Soil water repellence severity was determined using the "Molarity of an Ethanol Droplet" (MED) test (King, 1981; Doerr, 1998) at the soil surface and through the soil profile.
Vegetation and litter cover and height were assessed inside the micro- and macro-plots by visual field estimation drawing to a paper grid. Average surface, height and depth were calculated for n quarters of the grid (34 for macro-plots and 25 for micro-plots). Litter

depth was estimated through a set of measurement inside the plots, estimation of deep was realized inserting a simples ruler stick inside the litter as a not destructive method. Litter water retention was calculated in the base of 3 to 4 square undisturbed litter samples of 25cm side by site. Samples were then dried at 105ºC, weighed, then water saturated by total immersion during 2h water and then dripped and weighed (Table 1). Litter water retention is calculated as the difference between dry and drained weight of each sample divided by the surface sample.

3.2.4. Data analysis

A battery of site-related (years from ploughing, plot surface, exposure, slope), soil-related (BD.0_5cm.gcm3, Stonines.0_5cm%weight, OM%, Penet_kgm-2, Torvane_Kgcm3), cover-related (Cover_veg%, Cover_litter%, Cover_stones%, Cover_bare%, DepthVeg.cm, DepthLitter.cm), soil moisture related (Initial soil moisture at each one of four soil depths with the PR probe (InitSM.PR.0-10 to 30-40), at each one of five soil depths with the ML probe (InitSM.ML.0-5 to 40-50), final soil moisture at each one of four soil depths with the PR probe (FinalSM.PR.0-10 to 30-40) and SWR-related factors (SWR on the litter layer, on the soil surface, and six depths (0-5, 5-10, 10-20 to 40-50cm) were analysed via non-parametric Spearman correlation coefficient for addressing its relation with the overall figures of OLF (mm) for the entire rainfall simulation and annual OLF values (mm) for the microplots. In the case of the annual OLF values (mm) for the macroplots and micro and macroplots set together, only the site, soil and cover-related explanatory variables were tested. Only the significant explanatory variables ($P \leq 0.05$) and some interesting correlations were showed. Additionally, Spearman correlations coefficients were also obtained for the weekly Rainfall amounts and the weekly PR soil moisture values measured at each one of four depths (0-10 to 30-40cm) for both OLF (mm) and OLF coefficient (% of rainfall).

3.3.Results

3.3.1. Rainfall

The hydrological year 2006-2007 with 1667mm of rainfall was 18% wetter that the 12-years average (1403 mm) (Figure 3). About 70% of the annual precipitation fell between October and February, and this wet season was rainier than the average, with the exception of a January exceptionally dry. The dry season was slightly less rainy that the 12-years average except for a June exceptionally wet. A total of 120 rainy days (>1mm) were recorded, including a maximum daily amount of 73mm, 2 days with daily amount higher than 60mm and 15 days higher than 30mm. In comparison, the 12-years average rainfall presented 107 rainy days, a maximum daily amount of 80mm, 1.5 days with daily amount higher than 60mm and 10 days higher than 30mm.

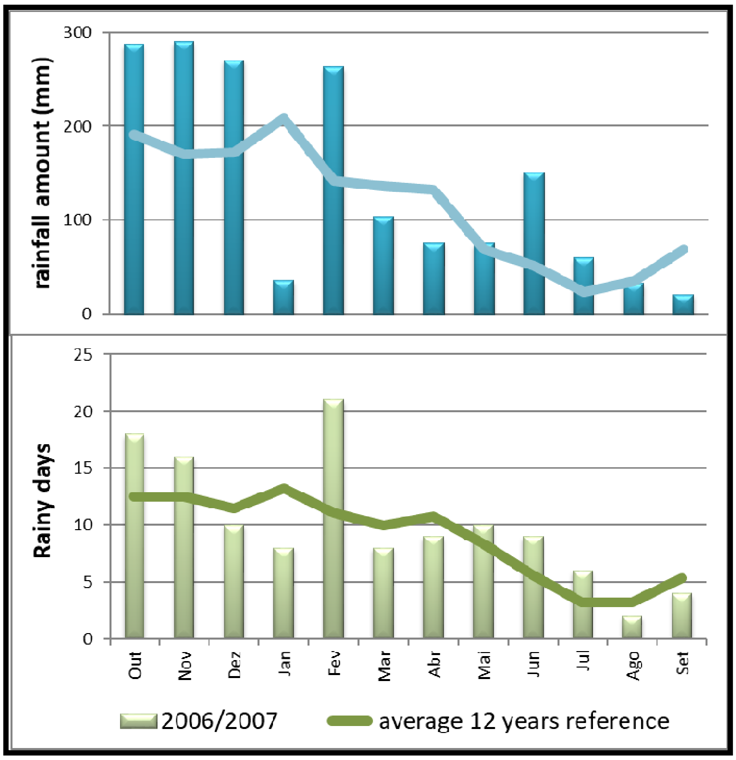


FIGURE 3. *RAINFALL CHARACTERISTICS – AVERAGE MONTHLY PRECIPITATION AMOUNT AND RAINY DAYS FOR THE 12 YEARS REFERENCE PERIOD COMPARED WITH THE STUDY EAR PERIOD 2006-2007*

3.3.2. Soil Moisture

Concerning rainfall simulation experiments, soil moisture content at the soil profile (0-40cm) was consistently lower in the R1 site at the beginning of the RSE (pre) in comparison with the R2 and R3 sites (Figure 4a). At the end of the RSE, the R2 and R3 sites still exhibited soil moisture through the soil profile higher than at R1. Despite a higher initial soil moisture at the R2 site, at the end of the RSE, soil moisture values were similar for both sites. However, after a draining period of 1 hour, R2 maintained a higher moisture content than R3.

R1 site showed a uniform SM increase for the 4 soil layers at the end of the RSE's as R2 and R3 sites presented a higher increase in soil moisture at the 20cm deep layer. After 1 hour drainage the 20 cm layer also suffered a more severe drainage and soil profiles recovered more homogeneous soil moisture pattern.

The annual mean soil moisture content (0-40cm) was similar for the 3 rotations at about 5 %, slightly higher for R2 that clearly presented a larger standard deviation of 6.5%. In terms of average SM content through the soil profile there was a significant decrease of SM between at 20cm deep and then a progressive increase with depth. (Figure 5ab).

The weekly mean SM contents increased significantly after important rainfall events (exceeding 150mm per week) or following long wet periods, and showed very similar moistening pattern for the 3 plantations. The surface soil layer underwent larger variations in soil moisture content, and in some occasion during the wet period, the deeper layer also suffered a large increase after intense rainfall. The evolution of soil moisture content during the year for the 3 plantations is very similar, the plantation R2 suffered a higher weekly variation, exhibiting the lower SM content during the summer period and a higher content during the wet period. The drying process differs between sites, as the R3 drop faster than the R2 and R1 (Figure 5cd).

The annual mean soil moisture by soil depth (0-40cm) was very similar for the 3 plantations sites though the R2 site showed the highest soil moisture at the top soil depth and lower at 30cm depth (Figure 4b). Although slight differences were registered between soil depths, there was a tendency for lower soil moisture at 20 cm depth. These tendencies were also observed during the driest and wettest periods (Figure 4b).

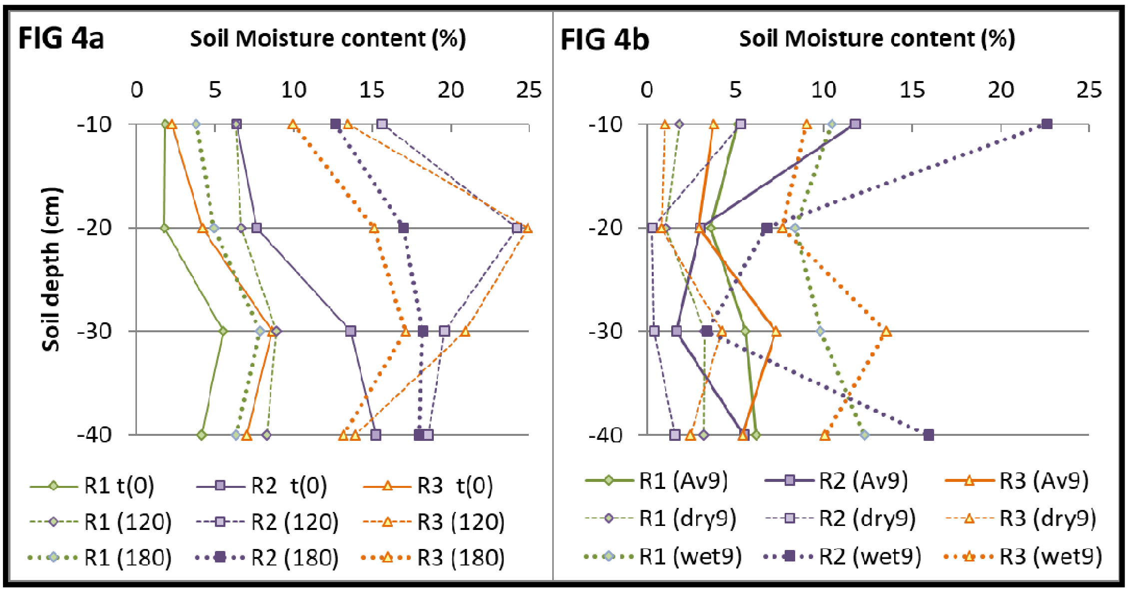


***FIGURE 4** – 4A SOIL MOISTURE PROFILE AT THE BEGINNING OF THE RSE T(0) AT THE END OF THE RSE T(120) AFTER ONE HOUR OF DRAIN T(180) ; 4B AVERAGE ANNUAL SOIL MOISTURE PROFILE (AV), AVERAGE SOIL MOISTURE PROFILE FOR A DRY PERIOD ON 03/05/2007 (DRY) , AVERAGE SOIL MOISTURE PROFILE FOR A WET PERIOD ON 15/02/2007 (WET) FOR THE 3 PLANTATIONS R1, R2 AND R3*

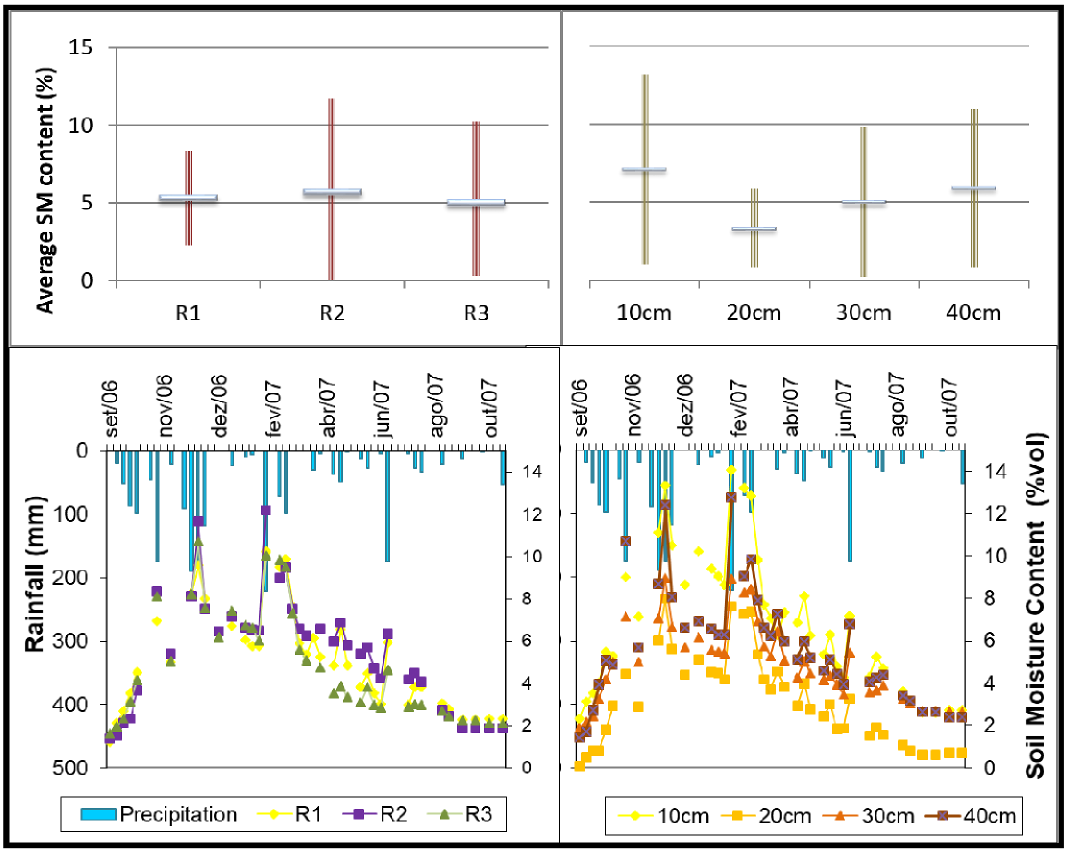


FIGURE 5 - SOIL MOISTURE PROFILE CHARACTERISTICS – ANNUAL AVERAGE AND STD OF SOIL MOISTURE CONTENT DURING THE STUDY YEAR 2006-2007 5A) PER PLANTATION R1, R2 AND R3 5B) PER DEPTH (10CM; 20CM; 30CM; 40CM)- WEEKLY AVERAGE SOIL MOISTURE CONTENT DURING THE STUDY YEAR 2006-2007 5A) PER PLANTATION R1, R2 AND R3 5B) PER DEPTH (10CM; 20CM; 30CM; 40CM).

3.3.3. Hydrological Response

3.3.3.1. Simulated Rainfall on Micro-plots

The highest overall OLF coefficient of 40% was recorded at the R1 site, whereas OLF coefficient was about 30% for both R2 and R3 sites (Table 2). OLF start time was between 3 and 4 minutes after the beginning of the experiment for all 3 sites. The temporal evolution of OLF generation during the rainfall simulations showed a strong increase during the first minutes, the R1 site achieved the OLF steady state in 10 minutes and in R2 and R3 the OLF is constant after 20 minutes of rainfall simulation (Figure 6). The OLF end time after the rainfall stopped was 3-4 minutes in the R1 and R2 sites, but in the R3 was 19 minutes.

TABLE 2 – OVERALL OLF RESULTS FOR THE 3 DIFFERENT MEASUREMENT METHODS AT THE 3 PLANTATIONS.

Method	Variables		R1 n	R1 mean	R1 sd	R2 n	R2 mean	R2 sd	R3 n	R3 mean	R3 sd
Rainfall simulations	Simulated rainfall	mm		**92**			**92**			**92**	
	OLF start time	s	*2*	**219**	± *72*	*2*	**240**	± 1	*2*	**200**	± 57
	OLF end time	s	*2*	**225**	± *21*	*2*	**245**	± 7	*2*	**1170**	± 42
	Mean Initial SM	% vol.	*32*	**3**	± *3*	*32*	**11**	± 12	*32*	**6**	± 7
	Mean Final SM	% vol.	*32*	**8**	± *3*	*32*	**20**	± 17	*32*	**18**	± 15
	Mean SM increase	% vol.	*64*	**4**	± *3*	*64*	**9**	± 9	*64*	**13**	± 11
	Overall OLF	mm	*2*	**36**	± *13*	*2*	**30**	± 1	*2*	**30**	± 17
	OLF coefficient	%	*2*	**40**	± *14*	*2*	**32**	± 1	*2*	**33**	± 19
	Natural rainfall	mm		**1857**			**1857**			**1857**	
Microplots	Overall OLF	mm	*2*	**423**	± *310*	*2*	**284**	± 34	*1*	**308**	± -
	OLF coefficient	%	*2*	**23**	± *17*	*2*	**15**	± 2	*1*	**17**	± -
Macroplots	Overall OLF	mm	*3*	**134**	± *120*	*3*	**90**	± 89	*3*	**9**	± 3
	OLF coefficient	%	*3*	**7**	± *6*	*3*	**5**	± 5	*3*	**1**	± 0

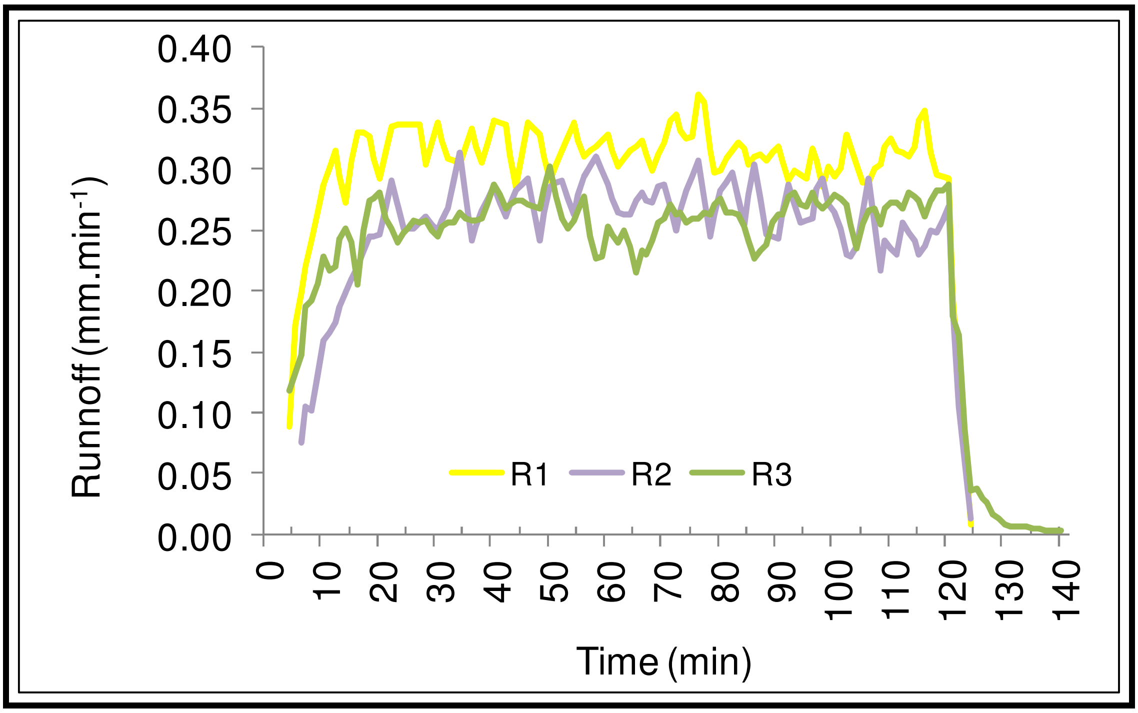


***FIGURE 6** – AVERAGE TEMPORAL OVERLAND FLOW RATE EVOLUTION DURING THE RSE'S PER PLANTATION R1, R2 AND R3.*

3.3.3.2. Natural Rainfall on Micro-plots

The annual OLF amount was higher at the R1 site in comparison with the R2 and R3 sites (Table 2). In terms of overall OLF coefficient the highest value was recorded at the R1 site with 23%, whereas OLF coefficient was about 15% for both R2 and R3 sites (Table 2). The weekly pattern in OLF amounts revealed that the R1 site has generally the higher response excepted for some exceptional weeks during the dry season (Figure 7d). About 56% of the OLF amount was produced during the beginning of the wet season (until December 2006), even if OLF coefficients were higher during the driest months, especially in the R1 and R3 sites (Figure 7b). The total OLF coefficient was higher at the R1 site, but OLF coefficient peaks were superior in the R2 or R3 site in some occasions, especially in the driest months. In fact, the maximum weekly OLF coefficient of 61% was registered at the R2 site, as it was registered 47% in the R1 site after 12 mm of rainfall (Figure 7b).

3.3.3.3. Natural Rainfall on Macro-plots

The annual OLF coefficient fell according with the rotation cycle, with values of 7%, 5% and 0.5% for R1, R2 and R3, respectively (Table 2). The weekly pattern in OLF amounts revealed that the R1 site had the higher response but the highest peaks were registered on site R2 (Figure 7c). About 76% of the OLF amount is produced during the beginning of the wet season (until December 2006), and the OLF coefficients followed that pattern. Nevertheless, at R1 site, many OLF coefficient peaks were also registered during the driest periods (Figure 7a).

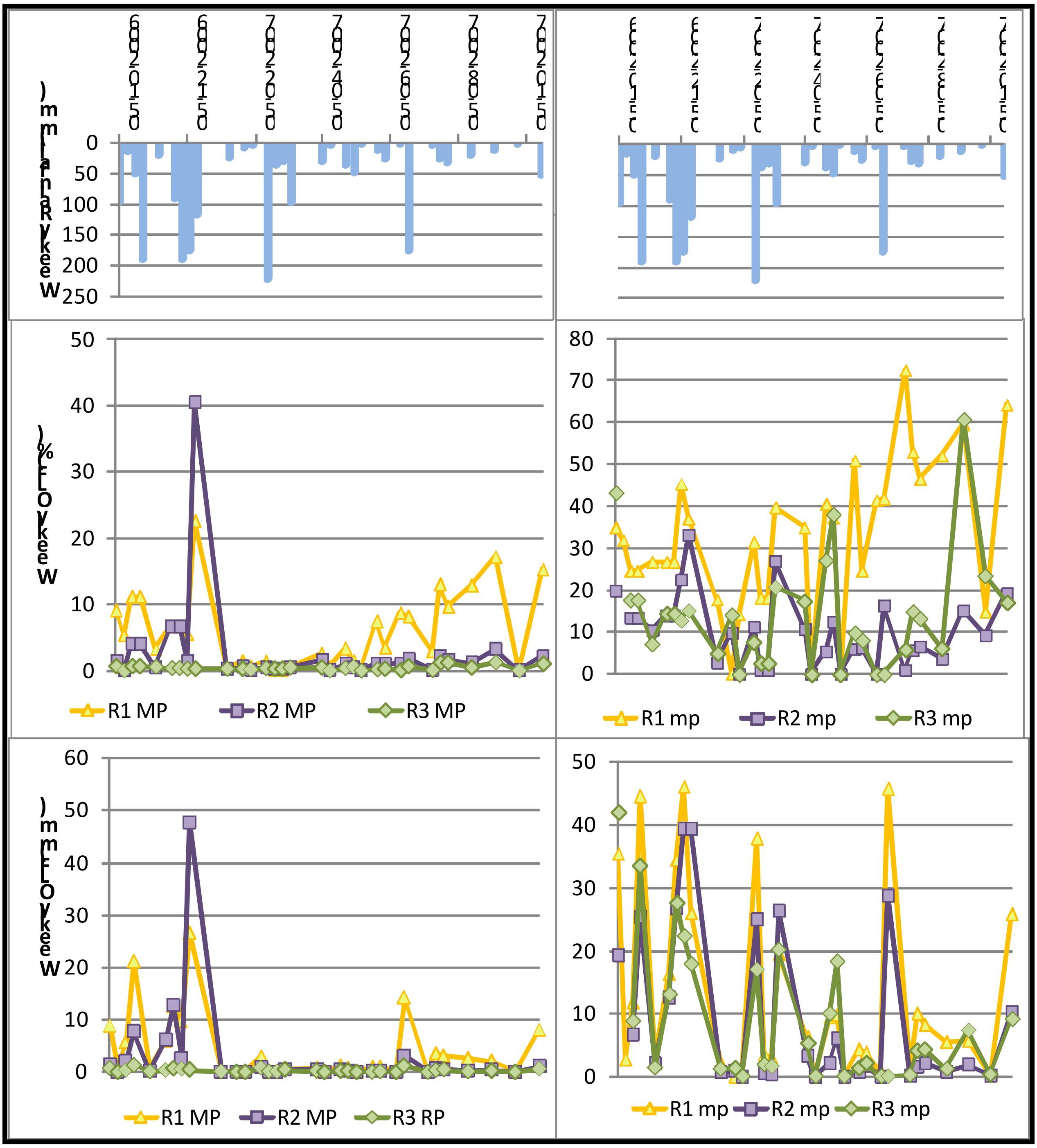


FIGURE 7 – WEEKLY RAINFALL AMOUNT (MM) AND WEEKLY AVERAGE OLF RATE (%) BY PLANTATION (R1, R2 AND R3) AT THE MACRO PLOTS SCALE (MP; 16M^2); WEEKLY AVERAGE OLF RATE (%) BY PLANTATION (R1, R2 AND R3) AT THE MICRO PLOTS SCALE (MP; 0.25M^2); WEEKLY AVERAGE OLF AMOUNT (MM) BY PLANTATION (R1, R2 AND R3) AT THE MACRO PLOTS SCALE (MP; 16M^2); (A) WEEKLY AVERAGE OLF AMOUNT (MM) BY PLANTATION (R1, R2 AND R3) AT THE MICRO PLOTS SCALE (MP; 0.25M^2).

3.3.4. Key factors

3.3.4.1. Rainfall simulation experiences

Some independent variables show significant Spearman correlations for explaining the total OLF produced from the rainfall simulations (Table 3). Topsoil stone content (stoniness.0-5cm %weight) and vegetation height showed a direct correlation, while soil moisture showed a consistent inverse correlation for all the instances (and significant for both at the beginning -InitSM.ML5-10cm and at the end of the rainfall simulation - FinalSM.PR.0-10cm, see Table 3). SWR on the litter layer and 0-5cm were also good explanatory variables of the overall OLF values.

Mean initial SM contents had also an influence on OLF amount and on the soil moistening patterns (Figure 8). In fact, the RSE’s performed on dryer soils (inferior to 5%) produced generally higher OLF amounts and lower soil moisture increases than the RSE´s performed over wetter ones.

TABLE 3 – SPEARMAN CORRELATIONS BETWEEN OLF OVERALL FIGURES (IN MM) AND OLF WEEKLY FIGURE (AMOUNT IN MM AND COEFFICIENT IN %) FOR JOINED MICROPLOTS AND MACROPLOTS (N=14 PLOTS, FOR 32 WEEKLY PERIODS) AND SELECTED INDEPENDENT VARIABLES. BOLD AND BOTH BOLD AND UNDERLINED ARE STATISTICALLY SIGNIFICANT (P < 0.05 AND P < 0.05 RESPECTIVELY)

		OLF overall figures				OLF weekly figures		
		SER	micro	Macro	m&M		m&M	m&M
	plot number	6	5	9	14		14	14
	OLF variable	mm	mm	mm	mm		mm	%
Independent variable		OLF amount (mm)				OLF amount (mm)		(%)
Site-related	Years from ploughing	-0.239	0.000	**-0.527**	-0.300	Rainfall mm	**0.685**	**0.445**
	Plot surface	0.314	0.100	**0.517**	**-0.495**	SM.PR.0_10	0.084	-0.012
Topsoil-related	Bulk density	0.586	-0.149	0.083	0.152	SM.PR.10_20	**0.265**	**0.146**
	Topsoil stoniness	**0.657**	-0.300	-0.200	0.057	SM.PR.20_30	0.057	0.012
	Penetration res.	0.314	0.000	**0.552**	-0.167	SM.PR.30_40	-0.043	**-0.157**
	Shear strength	0.257	0.100	0.042	**0.500**	-	-	-
Cover-related	Cover_veg%	0.486	-0.300	**0.494**	-0.084	-	-	-
	Cover_litter%	0.086	**-0.800**	-0.228	**-0.650**	-	-	-
	Cover_stones%	0.314	0.500	**0.527**	**0.501**	-	-	-
	Cover_bare%	-0.034	0.094	0.365	0.255	-	-	-
	DepthVeg.cm	**0.736**	**-0.738**	-0.188	**-0.745**	-	-	-
	DepthLitter.cm	-0.429	-0.100	-0.429	-0.387	-	-	-
Moisture-related	*InitSM.PR.0_10*	-0.143	-0.575	0.017	-0.432	-	-	-
	InitSM.PR.10_20	-0.371	0.247	**0.800**	0.038	-	-	-
	InitSM.PR.20_30	-0.406	0.209	-0.250	-0.164	-	-	-
	InitSM.PR.30_40	-0.429	0.164	-0.317	-0.294	-	-	-
	FinalSM.PR.0_10	**-0.714**	0.100	-	-	-	-	-
	FinalSM.PR.10_20	-0.486	0.575	-	-	-	-	-
	FinalSM.PR.20_30	-0.371	0.247	-	-	-	-	-
	FinalSM.PR.30_40	-0.600	0.575	-	-	-	-	-
SWR-related	SWR.Litter	**0.759**	-0.530	-	-	-	-	-
	SWR.surface	-0.383	-0.092	-	-	-	-	-
	SWR.0_5	**0.714**	-0.200	-	-	-	-	-

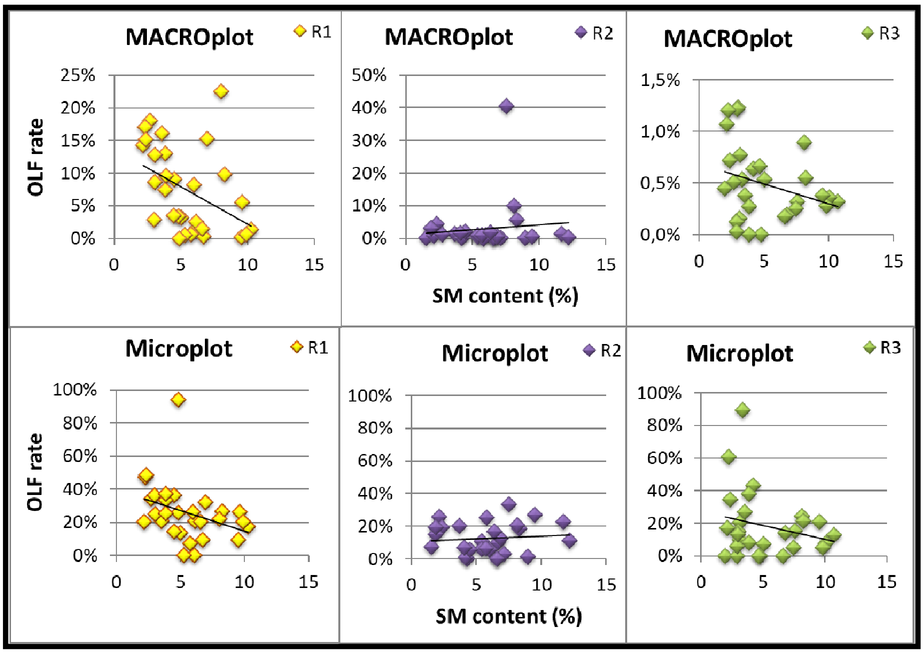


FIGURE 8 – MEAN SOIL MOISTURE AT 0-40CM (%) VERSUS OLF RATE AT EACH PLANTATION R1, R2 AND R3, WITH BEST-FIT LINEAR REGRESSION LINE (A) IN AVERAGE FOR THE MACROPLOTS ; (B) IN AVERAGE FOR THE MICROPLOTS.

3.3.4.2. Microplots

Only litter cover and vegetation depth were found to be marginally (due to the low number of plots) negatively correlated with the overall OLF figures on the microplots. The only other correlation was found with the level of soil moisture or SWR.

3.3.4.3 Macroplots

Overall OLF amount on the macroplots decreased with time from ploughing and soil penetration resistance. Despite its marginal statistical significance, direct correlations were found between annual OLF figures and vegetation cover, stone cover and soil moisture (PR tubes, 10-20cm) (Table 3).

Combining micro-plots and macroplots (m&M in table 3) highlights the negative and strong relations between OLF and plot scale, litter cover and vegetation depth, and the positive ones with shear strength.

The weekly OLF figures in absolute terms (mm) were strongly related with rainfall amount and one soil moisture (PR10-20cm), while the weekly OLF coefficient figures (in % of rainfall) were still significantly but worse explained by rainfall amount and by two soil moisture depths (PR10-20 and 30-40cm). The weekly OLF coefficients, both micro and macroplots, by site, exhibited a slight negative relationship with topsoil moisture (PR0_10cm; r:-0,019 p:0.84) and analysing the macroplots at each site, a strong negative correlation between soil moisture and OLF coefficient for the plantations R1 (Spearman r:

-0,33; p‹0,05;) and R3 (r:-0.18; p:0.2) is shown while there was a strong positive correlation for the R2 site (Spearman r:0,26 p‹0,05).

3.4. Discussion

3.4.1. Overall OLF rate vs plot size (surface 16m² vs 0.25m² or length 8m vs 0.5m)

Overall overland flow rates obtained during the study period at the plantation R1, R2 and R3 for the 3 methods of OLF measurement are presented as a function of the plot surface in figure 9a, table 2.

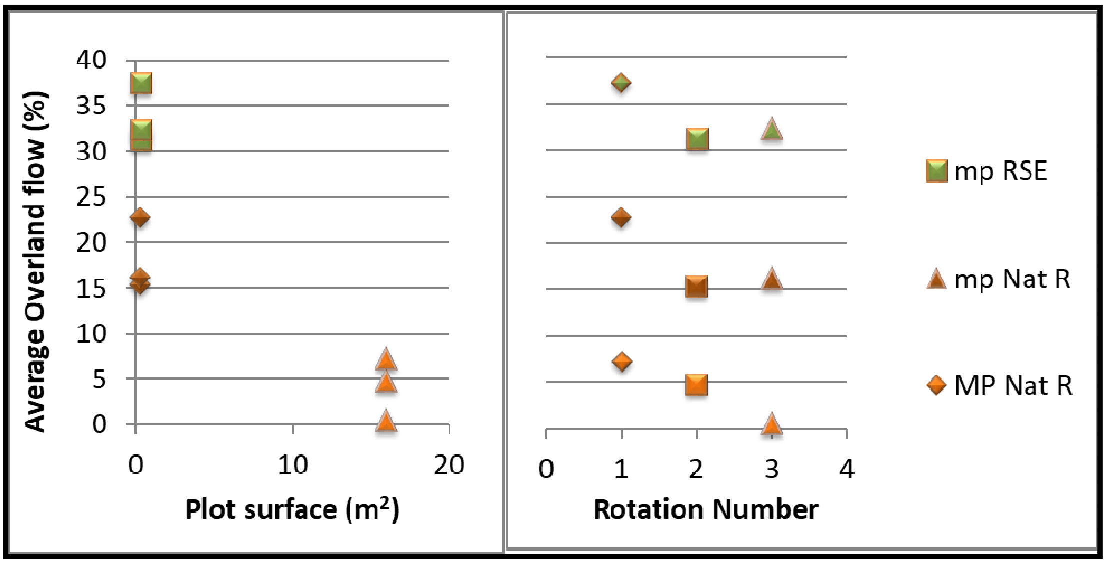


FIGURE 9 – OLF RATE VS METHOD VS ROTATION - FOR MICROPLOT OF 0.25M² WITH RAINFALL SIMULATION EXPERIMENT (MP RSE) ; MICROPLOT OF 0.25M² WITH NATURAL RAINFALL (MP NAT R) ; MACROPLOT OF 16M² WITH MATURAL RAINFALL (MP NAT R)

The lower OLF rates are produced for the larger plot size (16m²), between 0.5% at R3 and 7.2% at R1 under a total of about 1850mm of natural rainfall for the all study period of 13 months (table2). The smaller plots (0.25m²) produced higher OLF rate both under natural and simulated rainfalls. OLF rates produced at the microplot scale for natural rainfall amount varied between 15.3% and 22.8%. Under simulated rainfall with intermediate soil moisture conditions, OLF rates oscillate between to 31.3% and 37%.

Scale dependency of hydrological processes is an important issue, for instance in term of modelling, and in a general way lower OLF rates are commonly put in light at coarser scales (Boix-Fayos et al., 2007; Cantón et al., 2011 ; Stomph et al., 2002; Thomaz et al., 2012; Joel et al., 2002). In this study, variations in measurement methods as plot size verified to have also a significant impact on overall range of OLF rates. This output corroborated results of various authors in Portugal. Ferreira et al. (2008) gives evidence of more than 1 order of difference between OLF coefficient determined by RSE at microplot scale and OLF rate determined at larger plot scale of $16m^2$ for pine forest, shrubs and burnt areas. Prats et al. (2013) also noted a decrease of about 20% in OLF between microplots of 0.5m and 1m long in burnt pine plantations.

Scale dependency of OLF rate is generally explained as a function of a spatial or/and temporal variation in flow patterns.

As mentioned, during the rainfall simulation campaign on microplots, overland flow started within few minutes after the beginning of the simulation. The concentration time of flow for a distance of 50cm is extremely short and hydrologic connection is almost instantaneous. Longer slopes of 8m required much more time to develop connections. For short duration rainfall events, the concentration time needed for a continuous flow to attain the plot outlet may not be attained, the plot surface stays disconnected hydrologically from the outlet, and no OLF is collected. Yair et al. (2004) described a similar process for different slope length at catchment scale, where the contribution area to storm runoff was limited to the shorter slopes at the head of the catchment. Stomph et al. (2002) also presented a clear reduction in OLF with slope length increase specially with decreasing storm duration. Thomaz et al. (2012) found that small plots tend to have higher up to 45% more OLF than large plots. Nevertheless, during periods of greater rainfall volume, duration and intensity, higher OLF amounts were attributed to soil surface crusting in the large plots. Joel and al. (2002), put in light a consistent difference in OLF production with plot size (large plots yielded only 40% of OLF produced on small plots even in periods of continuous rainfall). Magnitude of OLF scale dependency is therefore also related to rainfall event characteristics.

The longer the slope, the longer will be the time for the water to have infiltration opportunities. Wainwright and Parsons (2002) suggest an alternative explanation, considering that scale dependency is the combined effect of temporal variation in rainfall intensity and run-on infiltration. Van de Giesen et al. (2000) put in light that for large runoff-producing events, the temporal dynamics of rainfall-runoff process determine the reduction of runoff coefficients from longer slopes. Van de Giesen et al. (2005) developed the concept of recession infiltration in which once the rain stops, water on long slopes has more opportunity time to infiltrate than water on short slopes. Van de Giesen et al. (2011) demonstrate that scale effect is maximum for moderate slopes (2-7%) and for a short high intensity rainfall event.

Scale dependency of OLF rate is also explained as a function of spatial variation in flow patterns. Thus, the longer the distance monitored, the higher the chances of flow discontinuity along the slope and the higher the chances of encountering areas with high infiltration rate.

Soil surface conditions can significantly influence the scale effect. Moreno-de las Heras et al. (2010) observed OLF decrease with increasing plot scale is lower for degraded soil. The study showed that OLF decrease is lower with increasing plot length for the R1 plantation. This plantation covered mainly by bare soil and stones, with weak understory vegetation and compacted soils, presented the most degraded conditions.

3.4.2. Overall OLF rate vs Rainfall Type (Natural Rainfall- 1850mm in 13 months vs Simulated Rainfall -92 mm in 2 hours)

Comparison of the OLF results obtained during the study period show OLF generation rates at microplot~~s~~ scale (using rainfall simulation), twice as high than under natural rainfall conditions, e.g.~~,~~ about 33% for RSE and 18% for natural rainfall.

In addition to scale dependency, rainfall characteristics also influence OLF coefficients. This study compares two set of data obtained for the same plots differing only on rainfall characteristics (natural rainfall and simulated rainfall). Simulated rainfall presents very distinct characteristics when compared with natural rainfall. For RSE's rainfall intensity is constant during two hours and much higher than for natural rainfall (it represented an amount of 92mm in 2 hours, while the maximum daily amount during the study period was 80mm). This difference between natural and simulated rain events was shown by Dunkerley (2008). High rain rates used for RSE, can be of limited relevance under ordinary field conditions. For infiltration studies performed at small-plot the use of constant rainfall intensity simulations may overlook important information and misrepresenting the mechanisms involved in OLF generation Dunkerley (2012)

Studies performed by Malvar et al. (2015) in burnt eucalypts, for a longer period, with the same methods show that RSE's experiments provide, in total for the study period an overall OLF rate under simulated conditions 2 time higher than OLF rates for natural rainfall (45% vs 22%). It seems that even if there is a difference in OLF rate between the two methods, this ratio is kept constant through various land uses and management. These findings revealed that simulated rainfall experiments are suitable to give information about variability inter-plots, in relative term, even if they do not produce the ratios of OLF produced by natural rainfall.

3.4.3. Temporal behavior of OLF rate vs plot size

Overall overland flow rates are presented as function of plantation type in the figure 9b. Measurements performed with identical plot size presented a similar evolution of OLF pattern following the ageing of the plantation (microplot scale for natural and simulated rainfall). Measurements performed with larger size plots show different temporal pattern (macroplot scale for natural rainfall).

Microplots, whether under natural or simulated rainfall, show a clear decrease in OLF rate between R1 and R2 (22.8% to 15.3% for natural rainfall and 37.5 to 31.3 % for RSE),

whereas no significant decrease is register between R2 and R3 plantation, that show even a small increase (15.3% to 16.2% for natural rainfall and 31.3% to 32.3% for RSE).
At macroplot scale, annual OLF rates decreased gradually with plantation age from 7% for R1 to 4.8% for R2 to 0.5% for R3.

3.4.4. Temporal behaviour of OLF rate vs rainfall type

The 2 methods, natural and simulated rainfall, presented a similar evolution pattern of overall OLF rate plantation age at microplot scale. Both methods present similar decreases of OLF rate between R1 and R2 (respectively less 7.5% and 6.2% for R1) and an identical increase between R2 and R3 (near 0.9% for R2).
The type of rainfall (natural or simulated) influences the total amount of OLF produced for each method, but dos not influence the temporal pattern evolution of OLF generation as a function of plantation ageing.
Concerning the temporal behaviour of OLF according with the seasons (figure 7), macro-scale and micro-scale methods show the same temporal trend. Both macroplots (MP) and microplots (mp) registered an <u>increase</u> of OLF rate during the <u>dry season</u> for R1 and R3, with larger differences at microplot level. R2 macroplots (MP) and microplots (mp) show an inverse tendency, an increase of OLF rate during the <u>wet season</u> for R1 and R3, with larger disparities at microplot level, except for one extreme event for what macroplots presented a large OLF peak.
OLF amounts showed a large increase during the wet period for both methods. The ratio of the total OLF amount produced during the wet season at R1 and R3 is quite similar for micro and macroplot scale 60% vs 65% at R1 and 63% vs 58% at R3. Nevertheless, the R2 plantation showed different pattern, it exhibited an even greater difference between wet and dry season at macroplot scale (91 vs 9%) than at microplots measurements (74 vs 26%).
Scale effect lead to significant differences in the estimation of OLF absolute values. Nevertheless, the two methods (MP and mp) seem able to capture the general trend of OLF rate temporal evolution. The differences maintained the proportionality through time, and even if for the plantation R2, that presented a different behaviour, the two methods both demonstrate these differences.

3.4.5. Key factors in OLF processes for each method at the 3 rotation stages

Commonly the scale effect on infiltration is ascribed to the spatial heterogeneity of soils' properties, among others to slope angle, vegetation and macroporosity.
Generally, infiltration processes are highly influenced by **slope angle,** although contradictory results describing the effect of slope on runoff are reported in the literature (Chaplot and le Bissonais, 2000). Increasing slope angles are responsible for lower depression storage and ponding depth (Fox et al., 1997), while the higher OLF velocity

leads to lower infiltration opportunities. In this study, no clear relationship was found between slope angle and OLF production, but microplots with linear slopes exhibit higher infiltration rate than microplots with convex slope. It is probable than a longer slope at macroplot level will be more likely to present slope ruptures or some concaves areas.

Plant cover is generally considered as one of the main factor determining runoff rate within a given slope (Cerdá, 1998), preventing high OLF rates (Cerdá, 1999; Gomi et al., 2008; Arnau-Rosalen et al., 2008). Vegetation presence increases rainfall interception and retention (Llorens and Domingo, 2007). Considering the eucalypt canopy interception in the study area (about 10% of incident rainfall (Ferreira, 1996; Coelho and al, 2008) can represent a significant parameter of OLF mitigation. At the microplot scale for simulated rainfall, since it is technically impossible to install microplots including trees and larges shrubs, the tree canopy buffer effect is zero, and can explain in part the higher OLF for RSE.

In term of understory interception, it can be considered almost zero at the microplot level. For technical reason no microplot included large shrubs, only small heather with reduce interception capacity. The positive correlation found between OLF and vegetation depth is not very representative of the reality due to the very low percentage of vegetation cover considered (Table 3). At the macroplot level, understory interception cannot be neglected for R2 and R3, as half of soil surface is cover by shrubs of various height and density and can represent a significant interception of the incident rainfall.

Vegetation canopy interception acquires an enhanced importance during the dry season, when the canopy is able to dry after each single rainfall event, recovering its initial storage capacity. This can originate a stronger difference of OLF between microplot and macroplot scales during the dry season.

In what concerns litter interception, many time neglected, experiences at the laboratory, demonstrated that a decayed litter layer of 10 cm presented a water retention capacity of 30mm, which confirms the findings of Leighton-Boyce et al. (2007) in the field. The litter layer in opposition to the canopy dries slowly, and during the wet season doesn't represented a significant buffer effect. Nevertheless, during the dry season, with large interval between rainfall events, its role in reducing the amount of water entering the soil can become relevant. However, regardless of the litter cover and thickness inside the microplot, all the rainfall simulations started to present OLF after a couple of minutes even for microplots presenting a homogeneous and thick decay litter layer. OLF stabilizes very quickly. This fact means that OLF started before total saturation of the litter layer. Since OLF circulated at the interface between soil surface and decay litter layer, litter layer interception is not proportional to litter layer surface and deep, as calculated in the lab. In fact, statistically there is no strong relationship between litter depth and OLF rate.

Common for blue gum (Eucalyptus globulus) forests, the presence of **severe soil water repellency characteristics**, is considered an important factor enhancing OLF production, (Walsh et al., 1994; Ferreira et al., 2000; Doerr and Moody, 2004; Keizer et al., 2005b; Leighton-Boyce et al., 2007; Miyata et al., 2009; Malvar et al., 2013;) especially for dry periods (Doerr et al., 2000; Keizer et al., 2005a; Leighton-Boyce et al., 2005; Santos et al., 2013). There is a close relationship between soil moisture content and SWR characteristics severity (Santos et al., 2013). In term of infiltration, it is important to considerer the spatial homogeneity and severity of SWR (Doerr et al., 2000). SWR measurements show a large dichotomy of results for transitions period as spring and autumn, presenting areas completely repellent and others completely hydrophilic. During this transition period, a smaller spatial scale of measurement will reduce the need for such hypotheses about patchy hydrophobicity and lead to lower infiltration rate for these plots.

During the dry season, due to the presence of quite homogeneous severe SWR, **the role of macropores**, is preponderant in the infiltration processes and specially rootholes. During this period matrix Ks of soil is almost reduced to zero, as shown by Gosch (2012). Infiltration process is then lead by the presence of preferential shortcut as cracks and macropores (Ferreira et al., 2000). Heeren et al. (2015) found that macropores account for 84% to 99% of the total saturated hydraulic conductivity in alluvial floodplain of Oklahoma. If the macropores network, related principally with decayed and live roots, is not dense enough to be representative in a small plot, then infiltration rate will increase from the small to larger scale.

The **slope micro-topography** of the study areas is highly heterogeneous, recent or former tilling operations created large depressions and mounds along the slope. As suggest by Van de Giesen et al. (2000) a larger area often means a higher **chance of extreme values** and normally this reduces OLF. One of the macroplots of the study presented a large depression at its base and it never produced any significant OLF. In fact, the large storage surface at the outlet of the plot was able to infiltrate all the OLF produce in the macroplot. Due to the heterogeneity of slope topography to which macroplots are more prone, they present preferential infiltration areas, that are rare in microplots of regular topography. Nevertheless, extreme events can produce the opposite effect and increase substantially OLF. For instance, during the winter, under extremely wet conditions, soil profile can locally become saturated and produce saturation OLF. Two macroplots presented evidence of saturation OLF during the winter. One plot with very weak slope at the top of the slope produced saturated areas in an extreme event under very wet antecedent conditions, as the drainage capacity of the lower soil layers was exceeded temporally and macroplot produced an exceptional amount of OLF. Another plot located at a lower position in the slope produced OLF as return flow for the same period due to areas of reduced soil depth leading to a local resurgence of throughflow at the soil surface.

3.4.6. Soil moisture

Soil moisture measurements revealed low values trough space and time. Values published by Santos et al. (2013), measured continuously with a EC-5's at a similar eucalypt plantation at 2.5 and 7.5 cm depth, are similar during the dry season and slightly higher during the wet season. The method used may partly explain the low values. On the one hand, soil moisture measurement systems used during this study is sensible to air gaps. The profile-tube insertion in a very stony soil originated small stones movements creating artificial air gap around the tube. These small air gaps influenced the probe reading, resulting in an artificial decrease of soil moisture content results. The EC-5's design used by Santos et al. 2013 was a compact equipment that allowed measurements in almost undisturbed soils.

On the other hand, soil moisture measurements were done only once per week and it is important to consider that the soil presented a rapid drainage capacity as demonstrated by SM moisture measurement during one week after rainfall simulation experiments. SM measurements were mainly performed for soils already drained due to the delay between rainfall events and soil moisture measurements. This fact led to an underrepresentation of the highest values of SM content (only rarely registered) and therefore lower annual SM content values.

Nevertheless, the errors due to potential methodological problems do not explain completely the extremely low SM values. SM sample analyses done in laboratory confirmed the low SM content, even if the values are slightly higher than in the field.

The macro-topography is considered by Nyberg et al. (1996), as the cause of a large percentage of soil water content variability; a significant correlation between water content and elevation/slope was found. This correlation is not constant in time and evolves in function of the season. Famiglietti et al. (1998) demonstrated that under wet conditions, variability in surface moisture content is strongly influenced by porosity and hydraulic conductivity, while under dry conditions, correlations are strongest with relative elevation, aspect and clay content.

Measurements were performed at top and middle slope, generally considered dryer than downslope and near the drainage channels (Brocca et al., 2007). A combination of various factors is responsible for the general soil dryness. Generally, soil moisture spatial pattern is correlated with the specific contributing area, slope, the elevation and distance from the drainage channel. Measurements performed by Boulet et al. (2015) at the lower part of the slope revealed higher and more persistent soil moisture content. The study catchment also presented steep slopes where throughflow and water drainage top-down of the slope where important, a phenomenon also described by Nyberg (1996).

Study site soils stoniness frequently exceeding 50%. Highest outflow is predicted in soil with high stoniness (Hlaváčiková et al., 2015). A stony soil profile has a relatively low available retention capacity and though unsaturated hydraulic conductivity may be high, leading to faster infiltration front movement during rainfall.

The mean density of the trees in the study sites is about 1500 trees per ha, a very intensive forest management. This promoted a developed roots network, noteworthy when observing an open soil profile leading, which results in a high water uptake by trees roots. Eucalypt *globulus* stands evapotranspiration was estimated by David et al., 1997 between 0.5 and 3.6mm per day. Forrester et al., 2010 calculated that transpiration of Eucalypt *globulus* stands attained it maximum rate for 5-7 years old plantations losing about 1.6–1.9 mm day^{-1}. Fabiao et al. 1995, demonstrated that for non-irrigated conditions, half of the eucalypt fine roots are located in the first 20cm of soil, and root density decrease with soil depth.

In this study, mean annual SM content can be related to root density. It decreased significantly at 20cm depth and then suffered a slight increase of soil moisture with soil depth. The increase of SM content at the soil surface is directly correlated with rainfall amount, the soil surface layer exhibits great variations of SM content, undergoing quicker and larger moistening during the rainfall event but also the faster drying due to the exposure to transpiration and direct evaporation of the soil surface.

Direct field observations confirmed the presence of wide soil areas totally dry along the soil profile, generally associated with the presence of severe soil water repellence at the soil surface or at intermediate depths, while the soils' deeper horizons are generally more retentive. Throughout the year there are large portions of the soil matrix that almost never get wet. The water circulation in the soil occurs mainly through preferential ways along the roots, stones, cracks, micropores and macropores. The observation of a vertical soil profile opened after two hours of rainfall simulations (92mmof rainfall with less of 30% of OLF) showed very irregular wetting front whose depth varied between 10 or 20 mm. Only some signs of wetness were visible deeper in the soil profile, generally associated with the presence of roots. The large amount of water discharge during the RSE seemed almost invisible or concentrated in very restricted areas not observable at the soil profile.

RSE performed for very dry initial SM content showed a global increase of SM content along the soil profile much lower than the theoretical SM predicted with the infiltration rate. Soils are generally quickly drained through preferential ways and large part of the soil matrix are not evenly wetted.

3.5. Conclusions

The overall objective of this work was to determine the impact of rotational management practices on overland flow generation by comparing three successive eucalypt stands rotation cycles, namely a recently ploughed and planted- first rotation (R1), a young regenerated-second rotation (R2) and a mature regenerated- third rotation plantation

(R3). Different methodologies were used to measure overland flow (OLF): (i) simulated rainfall on micro-plot (0.28 m^2); (ii) natural rainfall on micro-plots; and (iii) natural rainfall on macro-plots (16m^2) to: (i) establish overall OLF values; (ii) determine the temporal pattern of OLF and; (iii) identify key factors in OLF generation; for each of the three rotation cycles and for each methodology.
* Overall OLF values at the three successive eucalypt stands rotation cycles suffered variation in function of the measurement method adopted. The R1 plantation always presented higher OLF rates comparatively to R2 and R3. (40% vs 32% and 33% for RSE, 23 % vs 15% and 17% for microplot and 7% vs 5% and 1% for macroplot). The plantations R2 and R3 presented similar OLF rate between them at the microplot scale for natural or for simulated rainfall. The plantation R3 presented a much lower rate than R2 at the macroplot scale.
* The rainfall type influenced the overall OLF rate, RSE produced OLF rate two time higher than natural rainfall, and this ratio is observed at each 3 three eucalypt stands rotation cycles.
* The plot size influenced the OLF rate, larger plots recorded at their outlet significantly lower OLF that smaller plots.
* Seasonal OLF rate, followed the same temporal trend at microplots and macroplot scale for the 3 three eucalypt stands rotation cycles. Both macroplots (MP) and microplots (mp) registered an OLF rate increase during the dry season for R1 and R3, with larger disparities at microplot level. R2 at macroplots (MP) and microplots (mp) showed an inverse tendency.
* Seasonal OLF amounts increased during the wet season for both methods. The total OLF ratio produced during the wet season at R1 and R3 is quite similar at micro and macroplot scale (60% vs 65% at R1 and 63% vs 58% at R3.) R2 showed a drastic difference between wet and dry season, more pronounced at macroplot scale (91 vs 9%) than for microplots measurements (74 vs 26%).
The two methods (MP and mp) are able to capture the general trend of OLF rate temporal evolution. The differences maintained proportionality through time, and even if for the R2 plantation, that presented a different behavior, the two methods are able to show these differences.
These findings reveal that rainfall simulation experiments are suitable methods to provide information about inter-plots variability under natural rainfall even if they do not produce the ratios of OLF produced by natural rainfall.
*In term of key factors, plot length has the more significant effect on OLF rate due to the higher spatial and temporal variability of infiltration for larger plots.
- Plantation age is the second more important factor, the R1 plantation presenting in all case the higher OLF rate.

- Soil moisture content is the main factor driving temporal pattern of OLF. Soils at the three plantations presented extremely low overall soil moisture content at the soil surface but also at the deeper layer (about 5%).

Soil moistening was slow and soils only remained moist for long rainy periods. Soil presents a very fast drainage capacity, due the presence of large areas of soil presenting high SWR along the soil profile and leading to a quick circulation of water through preferential way (e.g. macropores or roots channels). Soils presents an indirect low retention capacity. Regular soil matrix moistening is rare due to the presence of large areas with severe SWR characteristics along soil profile. The dryer layer 20cm presents the higher root~~s~~ concentration.

Soil Moisture content is a key factor in OLF production. During the dry season, the appearance of SWR due to the soil drying lead to a significant increase in OLF rate at microplot and macroplot scale for the R1 plantation. Nevertheless, due to the reduced amount of rainfall this do not increase significantly the overall OLF amount. During the wet season the three plantations showed the higher amount of OLF at micro and macroplot scale. At the microplot scale OLF amount are more even distributed through time. At the macroplot scale it is concentrated in extreme events, corresponding to saturation OLF conditions.

- Stone cover presented a positive relationship with OLF rate e amount.

- A negative relation exists between litter cover and OLF, the litter plays an important buffer effect, nevertheless during the dry season the buffer effect is reduced due to the litter severe WR characteristics, inducing OLF generation before saturation of the litter layer is attained.

3.6. References

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Chapter 4

Hydrological processes characterization in two forested headwater catchments (Eucalypt and Pine) in a wet Mediterranean mountain range.

Hydrological processes characterization in two forested headwater catchments (Eucalypt and Pine) in a wet Mediterranean mountain range.

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Abstract

Mediterranean headwater catchments have experienced major land-use changes in recent centuries, mostly characterized by increasing natural vegetation as a consequence of agricultural land abandonment or the afforestation of unproductive lands with fast-growing tree species. To assess the implications of land use in the hydrological processes an analyse of the hydrological response of two forested catchments with *Pinus pinaster Aiton* (LOU) and *Eucalyptus globulus Labil*. (SDC) was performed. It described rainfall patterns and the hydrological response in terms of streamflow of the two catchments and then identified correlations between the hydrological of the catchments and rainfall amount and distribution, evapotranspiration, soil moisture, overland flow, and land cover. Annual streamflow (Q) varies by a factor of 6.5 between years, LOU presenting a larger variation than SDC. The Runoff coefficient is higher for wetter years with a maximum of 58% for Lou and 61% for SC and decreases substantially for the driest year to 17% for LOU and 22% for SC. Annual evapotranspiration (ET-mm) is relatively constant through the six years of study and not influenced by the total rainfall amount. The average ET of LOU (907 mm) is much higher than for SDC (739mm) indicating the importance of forest type with pine consuming much more water than eucalypt stands. This to some extent contradicts the idea commonly accepted in society on the *Eucalyptus globulus* water consumption, and needs to be explored in further study.

Keywords

Afforestation, hydrological processes, paired catchments, wet Mediterranean, Pinus pinaster Aiton, Eucaliptus globulus Labil.

4.1. Introduction

Mediterranean headwater catchments have experienced major land-use changes over the last century, mostly characterized by increasing natural vegetation as a consequence of agricultural land abandonment (Beguería et al., 2003, Debussche et al., 1999, Lasanta-Martínez et al., 2005). This trend continues as the increasing demand for wood products and the growing pressures generate an increasing worldwide interest in the afforestation of unproductive lands with fast-growing tree species (Lafleur et al., 2013). FAO (2001) predictions indicate that plantations will cover 5 to 10% of the world's forested land area and that close to 50% of commercially harvested wood will come from these plantations. On the other hand, global climate change could lead to a much drier climate in the Mediterranean basin (Giorgi and Lionello, 2008), therefore threatening existing forests that are highly sensitive to the region's strong aridity gradient (Barboni et al., 2004). Both large-scale afforestation and deforestation could have major impacts on the hydrological cycle (Zhang et al., 1999). This highlights the importance of a detailed process-based understanding of the relationship between land use, and especially forests, and the water balance in this region.

There has been extensive research on the processes behind the impacts of land-use changes on the hydrological cycle and erosion (Garcia-Ruiz and Lana-Renault, 2011). In the Mediterranean region, most of these studies had been developed in abandoned agricultural lands in north east Spain (Llorens et al., 1992, Ruiz-Flano et al., 1992, Gallart et al., 1994, Llorens et al., 1997, Gallart and Llorens, 2004, Lasanta-Martínez et al., 2005, López-Moreno et al., 2006, Latron and Gallart, 2008, Seeger and Ries, 2008) southern Spain (Cerda, 1997, Cammeraat et al., 2005), France (Piegay et al., 2004, Bakker et al., 2008), and Greece (Koulouri and Giourga, 2007, Bakker et al., 2008). From the studies developed in Portugal, a few also addressed the implications of land abandonment (Bakker et al., 2008, Nunes et al., 2010, Nunes et al., 2011) but the majority concerned land-use changes after forest fires (Ferreira, 1996, Shakesby et al., 1996, Cammeraat and Imeson, 1999, Thomas et al., 2000, Coelho et al., 2004, Ferreira et al., 2005). Overall, there is a clear lack of data for the Mediterranean on the changes due to afforestation of agricultural lands and reforestation with different forest types.
Water yield variations due to land-use change at different spatial and temporal scales is also widely studied (Bosch & Hewlett, 1982, Hornbeck et al., 1993, Hornbeck et al., 1993, Sahin & Hall, 1996, Stednick, 1996, Brown et al., 2005, Cosandey et al., 2005,). According to Zhang et al. (2001), evapotranspiration is one of the main processes responsible for changes in annual water yield after alterations in land use. The influence of land-use changes on soil water movement (Edwards et al., 1976) leads to changes in the amount of water available for plant respiration, growth and evapotranspiration; catchment response to rainfall is also altered by the moisture status of soil surface (Edwards et al., 1976,

Tromp van Meerveld and McDonnell, 2005, Latron and Gallart, 2008, James and Roulet, 2009, Webb and Kathuria, 2010, Penna et al., 2011). Land use is also one of the most important factors controlling intensity and frequency of overland flow, due to differences in surface storage that change the partitioning between infiltration and surface runoff (Nunes et al., 2011). However, land use not only alters surface runoff processes but can also affect subsurface flow (Peters et al., 2003, Latron & Gallart, 2008).

Portugal is an illustrative case-study for Mediterranean afforestation. It is the European country where the transition from deforestation to reforestation was quicker (Pereira et al., 2009). The forest area was 4-7% of the Portuguese continental area in 1870 and, over a century, increased to more than 30% (Pereira et al., 2009). The afforestation plan supported the planting of 420.000 hectares of tree stands from 1938 to 1977, in particular with *Pinus pinaster Aiton* and *Eucalyptus globulus Labill* (Baptista, 1993, Coelho, 2003, Jones et al., 2011). These changes caused an important decrease of agricultural lands in favour of trees and scrublands (Daveau, 1995, Serra et al., 2008, Geri et al., 2010). The production of eucalypt in the coastal region of Central and North Portugal is double than pine (Soares et al., 2007). Between 1995 and 2010, eucalypt plantations in Portugal increased considerably in comparison with pine plantations and, in 2010, were the dominant forest type, occupying 812.000 hectares or 26% of the Portuguese continental territory (ICNF, 2013). Despite these large land-use changes and the widely-acknowledged relevance of forests for the overall availability of water resources in Portugal, the impacts of afforestation on the hydrological cycle continue poorly quantified (Pereira et al., 2009).

Moreover, climate projections for the study region foresee a pronounced decrease in precipitation, especially during the warm season, and a pronounced warming, with a maximum in the summer season. The inter-annual temperature variability is expected to increase, especially during summer, leading to a more frequent occurrence of extreme temperature events (Räisänen et al., 2004, Sanchez et al., 2004, Giorgi and Lionello, 2008, Nunes et al., 2013). In turn, these foreseen changes in climate will have noticeable effects on surface and ground water resources (Stigter et al., 2012, Nunes et al., 2013) and, thus, on water-related ecosystem services in the affected areas (Aguiar et al., 2009).

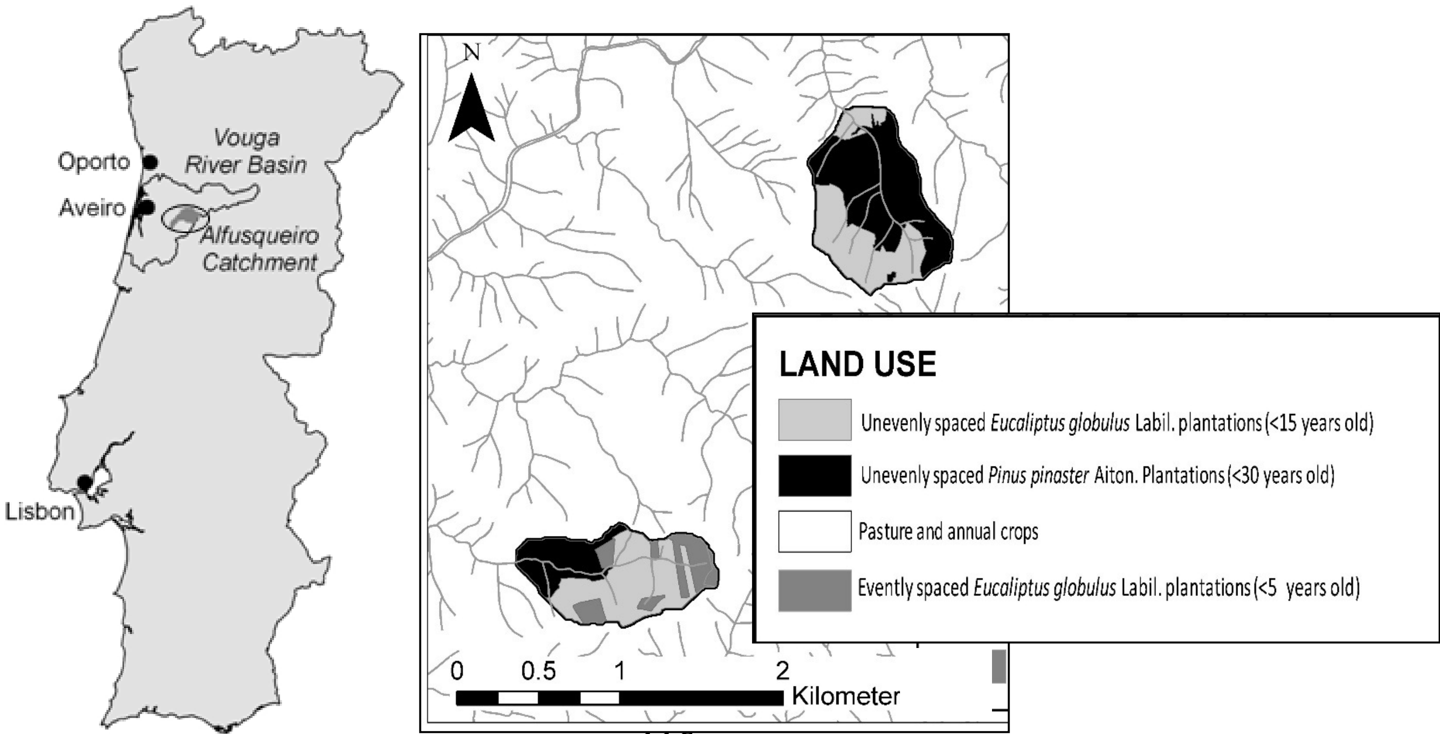
Comparison of paired catchments has been widely used to quantify the impacts of afforestation/deforestation on hydrological processes (Edwards et al., 1976, Bruijnzeel, 2004, Farley et al., 2005, Sun et al., 2006, Wang et al., 2008, Wei et al., 2008, Vanclay, 2009, Webb & Kathuria, 2010). This approach assumes that the principal components of the hydrological cycle can be measured with sufficient accuracy, so that the losses by evapotranspiration can be estimated for each of the catchments being compared. In the present study, two small headwater catchments are being compared, i.e. two forested catchments dominated by maritime pine and eucalypt plantations. These two experimental basins were compared for six contrasting hydrological years, (2010/16) with the aim of identifying possible relations between hydrological response of the catchments and the existing dominant land use, the amount of precipitation and the superficial soil moisture content. The differences observed in the catchments responses prompted an attempt to isolate the hydrological mechanisms that would explain the influence of land cover, precipitation amount and soil moisture content on the catchment hydrological behaviour.

4.2. Materials and methods

4.2.1. Study area

The two study catchments are located in the foothills of the Caramulo mountain within the Vouga River Basin (3600 km^2) in north-central Portugal (Fig. 1). The climate is wet Mediterranean with a mean annual precipitation of 1324 mm and an important inter-annual variability, ranging from 818 to 2127 mm for the period 2002-2016. It can be classified as dry-summer subtropical (Csb), according to Köppen's system (Hufty, 1984) with an average temperature above 10 °C during the warmest months (April to September) and a coldest month with an average temperature between −3 and 10 °C.

The Caramulo Mountains are a good case-study of hydrological impacts of afforestation (Ferreira et al., 2000, Shakesby et al., 2002. Jones et al., 2011). During the last decades, the Lourizela catchment (LOU) was extensively planted with *Pinus pinaster Aiton* and the Serra de Cima catchment (SDC) with *Eucalyptus globulus Labil.*



CHAPTER 4

***FIGURE 1**. LOCATION AND LAND USE OF THE THREE STUDY CATCHMENTS IN NORTH-CENTRAL PORTUGAL.*

4.2.1.1. Geomorphologic characteristics

Table 1 gives the main topographic characteristics of the two study catchments, expectedly determining their hydrologic response. The catchments differ in area (LOU>SDC), mean elevation (SDC>LOU) and mean catchment slope (LOU>SDC). The catchments' hypsometric curves (Howard, 1990) correspond to two different types (Fig. 2(a)): SDC reveals a convex curve, indicating a youthful stage; LOU corresponds to a transition between an s-shaped and a convex curve.

The lengths of the main streams are similar but their longitudinal profiles are clearly different, with LOU presenting a steeper slope than SDC. The main orientation of the catchments also differs, between SDC and LOU, which may be important for insolation and, thus, evapotranspiration as well as in case of moving storms (Nunes et al., 2006).

CHAPTER 4

TABLE 1. MAIN TOPOGRAPHIC CHARACTERISTICS OF THE TWO STUDY CATCHMENTS.

	P (m)	A (km2)	Hmax (m)	Hmin (m)	ΔH (m)	S (%)	O
LOU	4150	0.65	455	200	255	32	S-N
SDC	4020	0.52	485	273	212	28	E-W

	Tc (min)	L (m)	LFP (m)	Lk (m)	Sc (m/m)	DD	Or
LOU	31	1140	1342	835	0.171	1.29	2
SDC	34	1123	1434	921	0.142	1.78	2

P: Catchment perimeter; A; Catchment area; Hmax: maximum elevation; Hmin: minimum elevation; $\bar{H}$: Mean catchment elevation; S: Mean catchment slope; O: Orientation; Tc: Concentration time (Témez P., 1991); L: Main stream length; LFP: Longest flowpath; Lk: Total network length; Sc: Mean channel slope; DD: Drainage density (Strahler, 1964); Or: Order (Strahler, 1964).

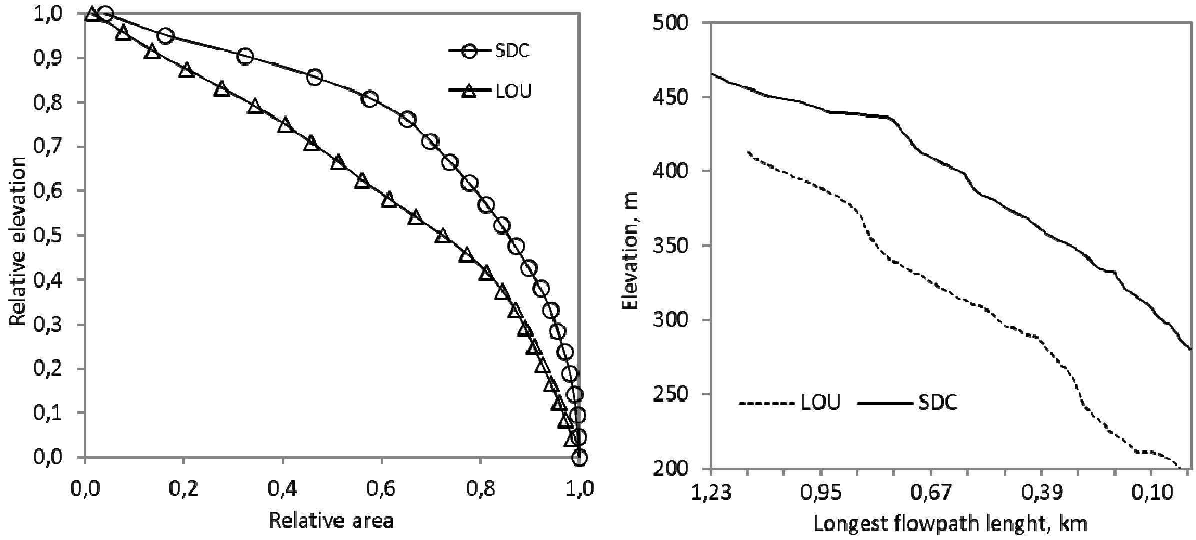


FIGURE 2. A) COMPARISON BETWEEN HYPSOMETRIC CURVES AND B) LONGITUDINAL RIVER PROFILES OF THE TWO STUDY CATCHMENTS.

4.2.1.2. Geology and soils

The geology in the study area is characterized by Paleozoic metasediments of the Schist and Greywacke Complex that were intruded by Hercynian granites (Van der Weijden and Pacheco, 2006). Schist is the unique parent material present in SDC and LOU.

The soils in the study catchments were identified based on an existing preliminary soil map (provided by IHERA; 1:25 000), in combination with field verification at 9 sampling points in SDC, 13 sampling points in LOU, part of which was accomplished by previous studies (van der Veur, 1993, Thomas, 1996, Boulet, 2011, Gosch, 2012). Soil profiles were described in the field and (re-)classified according with the World Reference Base for Soil Resources (WRB, 2007) (Table 2). Bulk density, organic matter and texture were determined for all sampling points, using standard laboratory methods.

The soils of all two catchments are (predominantly) Umbric Regosols. The Umbric Regosols of LOU are shallow, and closely approximate the threshold for Umbric Leptosols. Soil texture in both LOU and SDC was silt loam. Saturated hydraulic conductivity was high for and can be attributed to the presence of macro-pores in the forested soils, associated to their elevated stone content (Ferreira, 1996, Gosch, 2012). The Regosols and Cambisols of the two catchments did vary in their available water content (AWC), with lower values in LOU than in SDC, reflecting the coarser texture. At the catchment scale, total AWC is clearly lower for LOU (65 mm) than and SDC (143 mm, respectively), mainly reflecting the shallower soils of LOU. In terms of soil hydrological properties, it is still worth mentioning that the eucalypt and pine soils in the study area are well-known to frequently exhibit elevated levels of soil water repellency, especially during dry spells (,Ferreira et al., 2000, Coelho et al., 2005, Keizer et al., 2005, Leighton-Boyce et al., 2007, Boulet, 2011, Santos et al., 2013).

TABLE 2. SOIL TYPES AND REPRESENTATIVE CHARACTERISTICS FOR THE STUDY AREAS.

Catchment	Soil	Horizon	Depth (cm)	BD (g/cm3)	OM	Coarse	Sand	Silt	Clay	AWC	Ksat (mm/h)
LOU	Umbric Regosol	1	25	0.98	8%	43%	36%	52%	12%	0.26	70
SDC	Humic Cambisol	1	30	0.89	13%	18%	21%	56%	23%	0.33	70
		2	65	1.03	5%	14%	26%	55%	19%	0.33	-
	Umbric Regosol	1	35	0.98	13%	50%	23%	59%	18%	0.33	70

BD: Bulk Density; OM: Organic Matter; AWC: Available Water Content (pF 2.0 - pF 4.2)

4.2.1.3. Land use and vegetation

The current land use in the study catchments was characterized using aerial photography interpretation, completed with detailed field verification. The SDC catchment is dominated by eucalypt plantations, occupying 73% of the area, and the rest is covered by pine plantations; the opposite is true for the LOU catchment, with is pine plantations covering 61% of the area and eucalypt 39%.

The pine plantations in the study catchments are all composed unevenly spaced trees of over 25 years old, and have a well-developed ground cover, mainly consisting of litter (8-20 cm thick) and, to a lesser extent, shrubs (Table 3). The eucalypt plantations in the catchments, however, can be divided into three different types. The most common type is unevenly spaced eucalypt plantations, with trees aged under 15 years and an important component of ground cover provided by shrubs and litter (5-15 cm thick). This type includes the bulk of the eucalypt plantations in LOU, as well as two thirds of the plantation in SDC. The second and third types are eucalypt stands that were planted in 2010 respectively on terraced and flat terrain, respectively. They are restricted to SDC, occupying 7 and 15% of the total area. Both types are characterized by high percentage cover of bare soil and stones.

TABLE 3. MAIN CHARACTERISTICS OF THE FOREST PLANTATIONS IN THE THREE STUDY CATCHMENTS

		Tree characteristics			Ground cover			
Plantation type		Trees/ha	DBH (cm)	Height (m)	Litter	Vegetation	Bare soil	Stones
Eucalypt plantations	Unevenly spaced (<15 years old)	1600	9	9	26%	71%	4%	2%
	Evenly spaced, terraces (<5 years old)	1500	3	3	10%	5%	10%	75%
	Evenly spaced, flat terrain (<5 years old)	2600	6	3	13%	3%	64%	20%
Pine plantations	Unevenly spaced (>30 years old)	500	26	13	60%	40%	0%	0%

DBH: Diameter at Breast Height

4.2.2. Study period and hydro-meteorological data collection

During the study period, an automatic weather station recorded rainfall, solar radiation, air temperature, relative humidity, and wind speed and direction at 15-min intervals. The Pousadas station was located at about 3 km from the SDC and LOU catchments, at an elevation of 445 m a.s.l. Rainfall data at the weather station were used for SDC catchment. In addition to the weather station, a tipping-bucket gauge (with a resolution of 0.2 mm) was installed in LOU catchment that presented systematically total rainfall amount superior to SDC. The rainfall data of this gauge were used for LOU catchment.

Hydrometric stations at the outlets of the two study catchments recorded water level at 2-min intervals, using an ultrasonic level transmitter (Stevens 90841) in the case of LOU and a pressure sensor (Campbell Scientific CS450) in the case of SDC. These water level measurements were carried out in a cut-throat flume in LOU and SDC.

Topsoil moisture content was monitored in a continuous manner at one representative site within or adjacent to each of the two study catchments. These sites were a eucalypt stand within SDC and a pine stand next to LOU. The soil moisture readings were obtained with Decagon ECH2O EC-5 sensors, and stored at 15-min intervals in a DECAGON Em5b data logger. At the forested sites, 2 EC-5 sensors were installed at 2.5 depth and 2 at 7.5 cm.

4.2.3. Data analysis

The data analysis carried out in this study involved the following aspects:

Annual water balance calculation (Chow, 1964) to assess differences in evapotranspiration, streamflow and groundwater recharge;

Analysis of hydrographs to assess streamflow origins, using hydrograph separation techniques (Nathan and McMahon, 1990; Arnold et al., 1995);

Comparison of soil water patterns to assess the role of different vegetation covers on water balance.

4.2.3.1. Annual water balance calculation

Water balance components were analysed following the equation (Chow, 1964):

$R(mm)=ET(mm)+Q(mm)+Gs(mm)+\Delta S(mm)$ (Equation 1)

Where:

R: Rainfall.

ET: Evapotranspiration.

Q: Water yield.

Gs: Groundwater seepage.

ΔS: Soil and groundwater storage.

Knowing inflows, outflows and storage, a vegetation use and water storage component (including evapotranspiration, groundwater seepage and soil and groundwater storage) can be determined as the residual quantity needed to balance the continuity equation as follows (Chow, 1964):

$ET+Gs+\Delta S=R-Q$ (Equation 2)

As the study period comprises six hydrological years the assumption that soils have the same soil moisture at the beginning and end of the study period can be made, and the soil water storage and groundwater storage (ΔS) can be considered as zero. The value of groundwater seepage (Gs) was estimated as 5% of annual precipitation (ARHC, 2012).

4.2.3.2 Hydrograph analysis.

The 2 min hydrographs were separated into the two major streamflow components, surface runoff and baseflow, using an automated recursive digital filter (RDF) (Nathan and McMahon, 1990).

4.2.3.3 Streamflow analysis

The main streamflow events during the study period were selected and analyzed together with the associated rainfall events. Rainfall events were separated using a minimum inter-event time (MIT) of 6 hours, and those causing the main streamflow events in the catchments and with a minimum amount of rainfall of 10 mm were selected for analysis.

For each rainfall event the main characteristics were calculated: total amount of rainfall (Ptot, mm), maximum 30 minutes intensity (I30, mm/h), average event intensity (Ie, mm/h) and event duration (Pd, hr). Streamflow response at catchment scale for each rainfall event was separated into surface runoff or stormflow (SR) and baseflow (BF) as detailed above; the start and end of SR was used to separate the individual runoff events.

The main characteristics of all streamflow events computed were: total streamflow (Q, mm), surface runoff or stormflow (SR, mm), baseflow (BF, mm), runoff coefficient (RC, %), The relationships between all these variables were assessed using Spearman correlation coefficients.

4.2.3.4. Soil water patterns

The comparison of measured topsoil water patterns during the study period and their relation with the available water content was used as an indicator of the role of different land-cover types on water balance.

4.3. Results

4.3.1. Rainfall events characterization

This study concerns six hydrological years that contrasted in rainfall amount and distribution, one dry hydrological year (984mm), two regular (1259mm and 1372 mm) and four wet (from 1839 up to 2127mm), total rainfall amounts at SDC catchment.

Precipitation presented also differences between the two catchments (Fig. 3), with SDC registering lower values than LOU in all years.

LOU and SDC total rainfall amount are linked by the following equation: LOU = 1,185 SDC - 0,256 with R^2 = 0,979

There is a predominance of winter rainfall (41%), followed by autumn rainfall (24%), spring (24%) and a very dry summer (5%).

Rainfall events have been separated using a minimum inter-event time (MIT) of 6 hours, and events with a minimum amount of rainfall of 10 mm were selected for analysis.

This led to the selection of 216 events (table 4 a,b), on average 34 events per year with 31 events for the driest year and 44 events for the wettest year. There was a strong correlation of 0.92 between yearly total rainfall amount and number of events. There was an average total rainfall duration of 940 hours per year, with a large discrepancy factor of 2.2 between minimum and maximum duration respectively 670 hours and 1452 hours per year, as it was only a factor of 1.3 between max and minimum events number. The average daily amount for events superior at 10mm is about 32mm, with a minimum of 28 and a maximum of 38 mm relatively to annual values. The average event duration is about 1,2 days (min: 0.9 and maxi:1.4) with a I30 max of 10mm/h (mini:7.9 and maxi13.3).

In a general way, an increase of annual rainfall amount corresponds principally to a proportional increase in number of events per year and total hours of rainfall with Spearman correlation factors respectively of 0.92 and 0.90. There is a lower correlation with the increase in events duration (0.75) or rainfall intensity (0.70). It does not any relation with average I30max (0.14).

Considering the data set of individual events superior to 10mm, about 72% of the annual precipitation falls during events greater than 30mm representing 31% of the total number of events. The number of major events greater than 60mm is reduced (14% of the events) but nevertheless represents 43% of the annual amount of precipitation. Only the 3 wettest years recorded events with rainfall amount greater than 120mm, with two remarkable events above 300mm during winter 2015/2016. It exists a good correlation between annual total rainfall amount and % of annual rainfall amount falling during large events> 30mm and >60mm respectively 0.81 and 0.84. The correlation between annual total rainfall amount and number of large events > 30mm or > 10mm is weaker (0.63 and 0.66) indicated than an increase in total annual rainfall corresponds more to an increase of rainfall amount falling during large events (duration and/or intensity) than to an increase in number of rainfall events during the year.

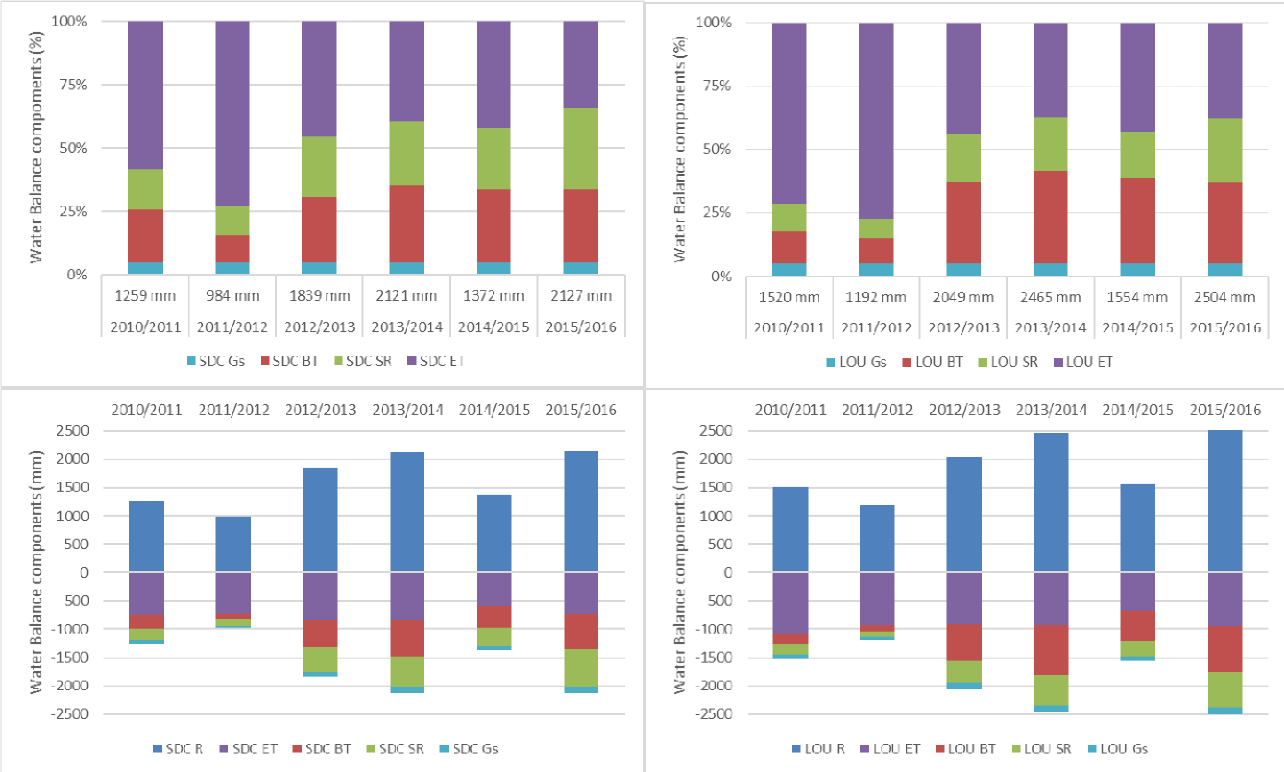


FIGURE 3. *WATER BALANCE COMPONENTS IN THE TWO CATCHMENTS A) IN MM; B) IN % OF TOTAL ANNUAL RAINFALL AMOUNT. R: RAINFALL, ET: EVAPOTRANSPIRATION, BT: BASE FLOW; SR SURFACE RUNOFF, GS: GROUNDWATER SEEPAGE.*

TABLE 4A. *RAINFALL EVENTS SEPARATION AND CHARACTERIZATION PER YEAR*

Year	Total Rainfall amount	Total Rainfall amount - event number >10mm	event number >10mm	Total rainfall duration	average rainfall intensity	average event duration	Average I30max	number events > 30mm /number events sup 10mm	% of annual rainfall amount for events> 30mm	number events > 60mm /number events sup 10mm	% of annual rainfall amount for events> 30mm
	mm			hours	mm/day	day/event	mm/h	n	mm	%	%
2010/2011	**1259**	**1026**	31	859	29	1,2	9,9	39%	54%	13%	27%
2011/2012	**984**	**790**	31	670	28	0,9	8,7	29%	38%	0%	0%
2012/2013	**1839**	**1278**	35	911	34	1,1	7,9	37%	47%	9%	24%
2013/2014	**2121**	**1821**	42	1452	30	1,4	10,2	48%	68%	26%	49%
2014/2015	**1372**	**1261**	33	969	31	1,2	13,3	48%	69%	18%	40%
2015/2016	**2127**	**2102**	44	1327	38	1,3	12,0	45%	79%	16%	55%
Correlation with total rainfall amount			0,92	0,90	0,70	0,75	0,14	0,63	0,81	0,66	0,84

TABLE 4B. RAINFALL EVENTS SEPARATION AND CHARACTERIZATION PER RAINFALL EVENT TYPE

		Total rainfall	Rainfall duration	average rainfall intensity	average event duration	Average I30max			Total rainfall	Rainfall duration	average rainfall intensity	average event duration	Average I30max
2010/2011	n	mm	days	mm/day	day/event	mm/h	**2013/2014**	n	mm	days	mm/day	day/event	Av I30max
Total > 10 mm	**31**	**1026**	**35,8**	**28,7**	**1,2**	**9,9**	**Total > 10 mm**	**42**	**1821**	**60,5**	**30,1**	**1,4**	**10,2**
> 120mm	0	0	0,0	0,0	0,0	0,0	> 120mm	4	562	17,0	33,0	4,3	15,2
120-60 mm	4	343	10,4	33,0	2,6	17,8	120-60 mm	7	478	16,4	29,1	2,3	9,6
60-30 mm	8	332	12,2	27,1	1,5	11,2	60-30 mm	9	398	12,8	31,2	1,4	11,6
30-10 mm	19	351	13,2	26,7	0,7	7,6	30-10 mm	22	383	14,3	26,9	0,6	8,9
2011/2012							**2014/2015**						
Total > 10 mm	**31**	**790**	**27,9**	**28,3**	**0,9**	**8,7**	**Total > 10 mm**	**33**	**1261**	**40,4**	**31,2**	**1,2**	**13,3**
> 120mm	0	0	0,0	0,0	0,0	0,0	> 120mm	0	0	0,0	0,0	0,0	0,0
120-60 mm	0	0	0,0	0,0	0,0	0,0	120-60 mm	6	551	13,9	39,5	2,3	19,6
60-30 mm	9	369	10,7	34,4	1,2	11,4	60-30 mm	10	394	15,7	25,1	1,6	13,3
30-10 mm	22	421	17,2	24,5	0,8	7,6	30-10 mm	17	317	10,8	29,4	0,6	11,1
2012/2013							**2015/2016**						
Total > 10 mm	**35**	**1278**	**37,9**	**33,7**	**1,1**	**7,9**	**Total > 10 mm**	**44**	**2102**	**55,3**	**38,0**	**1,3**	**12,0**
> 120mm	2	347	6,4	54,1	3,2	13,4	> 120mm	4	946	17,0	55,8	4,2	19,3
120-60 mm	1	90	2,1	42,8	2,1	12,0	120-60 mm	3	223	4,8	46,4	1,6	19,0
60-30 mm	10	420	12,3	34,3	1,2	10,7	60-30 mm	13	517	15,5	33,3	1,2	15,1
30-10 mm	22	421	17,2	24,5	0,8	8,7	30-10 mm	24	416	18,0	23,1	0,8	8,2

4.3.2. Annual Water balance

4.3.2.1. Inter annual variation

The study period covers a large range of annual total rainfall amount, varying by a factor of 2, from 984 to 2127 mm for SDC and 1192 to 2504mm for LOU, with respectively an average total rainfall amount over the six years of 1617mm and 1881mm. The year 2011/2012 can be categorize as a dry, the years 2010/2011 and 2014/2015 as medium, and the 3 others years as wet.

The annual streamflow amount (Q) exhibits also a larger variation between years by a factor 6.8 for LOU (208 to 1430 mm) and a factor of 6.0 for SDC (217 to 1291mm). The runoff coefficient is higher for wetter years with a maximum of 58% for LOU and 61% for SDC and decreases substantially for the driest year 17% for LOU and 22% for SDC (table 5).

The two components of Q, the Base Flow (BT) and the Surface Runoff or Stormflow (SF) follow the same tendency with a similar discrepancy between higher and lower flow, respectively a factor 7.6 for LOU BT (119 to 901mm) and factor 6.2 for SDC BT (104 to 641mm)

There is a linear correlation between the annual rainfall amount (R) and the total streamflow amount (Q). The annual streamflow amount increase linearly with the annual rainfall amount with a strong R^2 of 0.94 for LOU and 0.96 for SDC for the equation line. (figure 4)

The Runoff coefficient do not follow a linear relation with rainfall amount, it increases rapidly from 20% for driest years with about1000mm of rain to about 50% for medium years and then increase slowly to about 60%. (figure 4)

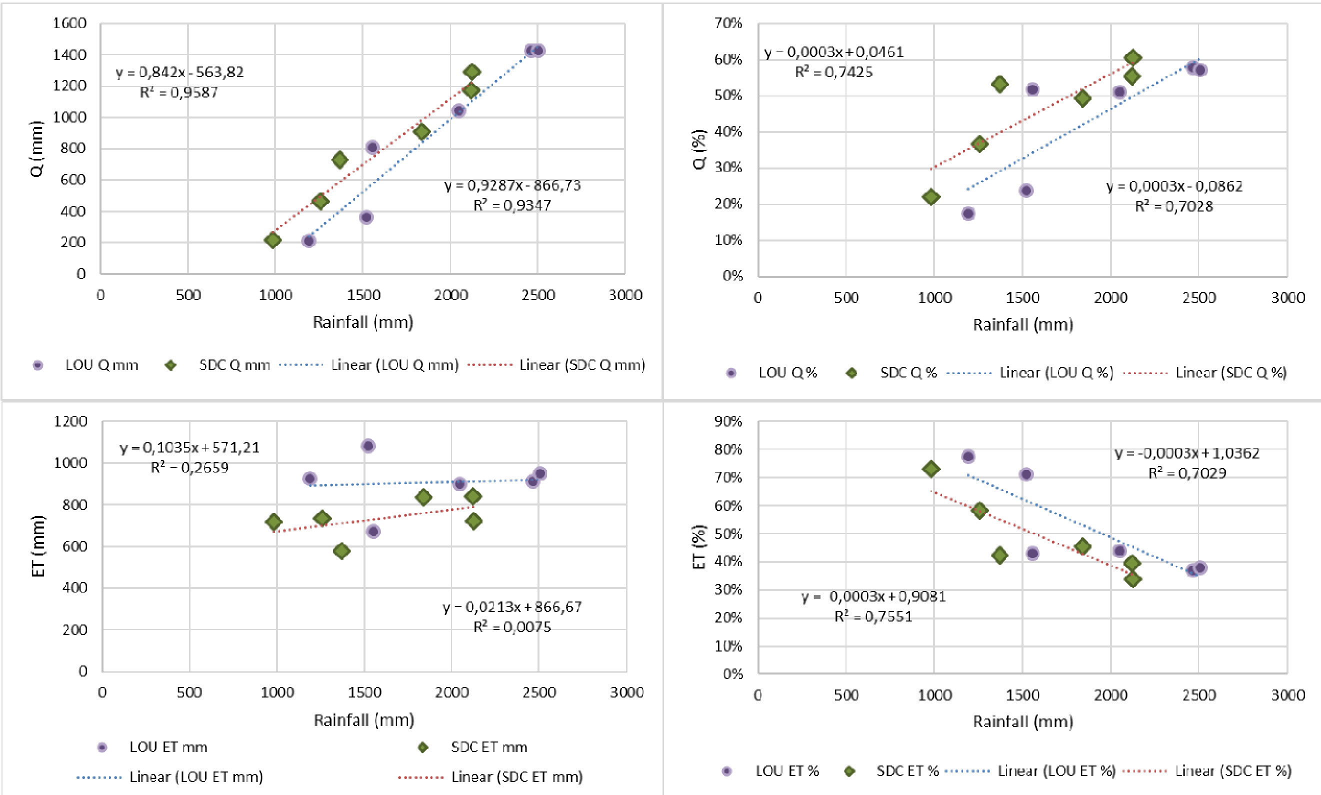


FIGURE 4. RELATION AND LINEAR EQUATION CURVE FOR LOU AND SDC OVER THE 6 STUDY YEARS BETWEEN TOTAL ANNUAL RAINFALL AMOUNT AND A) ANNUAL TOTAL STREAMFLOW (MM); B) ANNUAL RUN OFF COEFFICIENT (%); ANNUAL EVAPOTRANSPIRATION AMOUNT (MM); ANNUAL EVAPOTRANSPIRATION COEFFICIENT (%)

Annual ET amount is clearly independent from the rainfall amount, with very weak R^2 of 0.26 for LOU and 0.0075 for SDC obtained for linear equations (figure 5) Spearman correlation coefficient are also very low, 0.09 for LOU and 0.51 for SDC (table 5). In fact, the annual ET amount is relatively constant through the six years of study and not influenced by the total rainfall amount. The average ET for LOU is 907 mm with minimum of 670mm and maximum of 1082mm and for SC the average is 739mm with a minimum of 579mm and a maximum of 840mm (table 5). The year 2014/2015, presented an atypical low ET amount for both forest stands (670mm for LOU and 579mm for SC). This year was a regular year with a total rainfall amount of 1372mm for SC and 1554 for LOU, but with 55% of the annual rainfall concentrated in autumn.

Water consumption of the 2 forest stands was almost constant, indicating that no situation of real water stress happened even during the dry year. The ET demand of the forest stands was satisfied, the ET of Pine forest of about 900mm significantly higher that the ET from Eucalypt forest about 670mm.

In term of separation of annual total streamflow (Q) between base flow (BT) and surface runoff (SR), BT represents on average over the 6 years, 60% of the Q with a minimum of 53% and a maximum of 65% for LOU and 52% of the Q with a minimum of 48% and a maximum of 57% for SDC. Both BT and SR total annual amount show a very good correlation with total annual ainfall amount respectively 0.94 and 0.98 for LOU and 0.98 and 0.96 for SDC. Nevertheless, there is only a very weak correlation between total rainfall amount and ratio BT/SR, 0.19 for LOU and -0.03 for SDC as this ratio stays almost constant through the years for both sites.

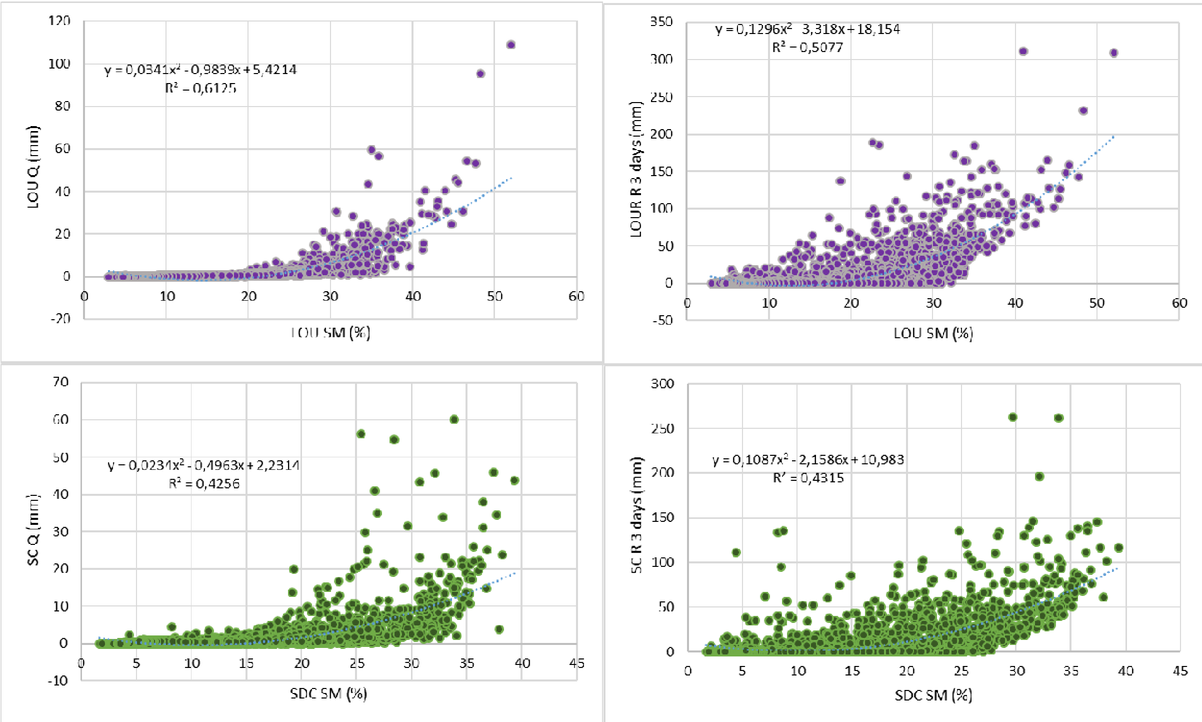


***FIGURE 5.** A) RELATION AND POLYNOMIAL EQUATION CURVE FOR LOU AND SDC OVER THE 6 STUDY YEARS FOR DAILY DATA SET BETWEEN TOTAL ANNUAL RAINFALL AMOUNT AND A) AVERAGE SOIL MOISTURE CONTENT (%) AND A) STREAMFLOW (MM); B) 3 ANTECEDENT PRECIPITATION DAYS; B) SPEARMAN CORRELATION COEFFICIENT / SOIL MOISTURE CONTENT / TOTAL STREAMFLOW AND ANTECEDENT PRECIPITATION INDEX.*

	LOU SM/Q	SC SM/Q	LOU SM/R	SC SM/R	LOU SM/API3	SC SM/API3
Correlation / SM	0,53	0,53	0,43	0,41	0,56	0,55

TABLE 5. WATER BALANCE COMPONENTS IN THE TWO CATCHMENTS A) IN MM; B) IN % OF TOTAL ANNUAL RAINFALL AMOUNT

year	LOU R mm	LOU Q mm	LOU BT mm	LOU SR mm	LOU BT %	LOU SR %
2010/2011	1520	361	190	172	53	47
2011/2012	1192	208	119	90	57	43
2012/2013	2049	1045	655	390	63	37
2013/2014	2465	1428	901	527	63	37
2014/2015	1554	807	528	279	65	35
2015/2016	2504	1430	795	635	56	44
Correlation / R		**0,97**	**0,94**	**0,98**	**0,19**	**-0,19**
year	SDC R mm	SDC Q mm	SDC BT mm	SDC SR mm	SDC BT %	SDC SR %
2010/2011	1259	463	262	200	57	43
2011/2012	984	217	104	113	48	52
2012/2013	1839	909	475	433	52	48
2013/2014	2121	1175	641	533	55	45
2014/2015	1372	731	394	330	54	45
2015/2016	2127	1291	618	680	48	53
Correlation / R		**0,98**	**0,98**	**0,96**	**-0,03**	**0,08**

4.3.2.2. Seasonal behaviour

Considering, total amount of Q over the 6 study years, a reduced fraction of the annual Q (16% for LOU and 14% for SDC) flows during the autumn, as 30% of the annual total rainfall amount (R) falls during this season, corresponding to Runoff Coefficient of 25% for LOU and 22% for SDC. (table 6a)

Winter is the wetter season, with 41% of annual rainfall. It is during this period, that the main part of the Q amount occurs, 56% for LOU and 55% for SDC, corresponding to great Qt rate of 64% for LOU and 68% for SDC. It is during this period that the streamflow response in term of amount and percentage is the most important.

For spring both Rs and Qs represent about 25% of the annual amount, with streamflow coefficients about 50% for both site.

Summer exhibits extremely low values only 5% of the annual rainfall amount and only 2 or 3% of the Q annual amount, both catchment drying up for several weeks during this period.

When separating between dry, medium and wet years, the Q partition per season differs sensibly. It is difficult to draw general conclusions for dry years, as the study period provides only a very atypical dry year, with a dry autumn and extremely dry winter. Nevertheless, it is clear that the streamflow rate response is very low for the autumn (about 6% for LOU and 8% for SC). In general term, there is a very good correlation for autumn season (0.86 for LOU and 0.92 for SC) between rainfall amount and streamflow rate for the 6 study years, the streamflow rate decreasing proportionally to seasonal rainfall amount (table 6b). The analysis of daily hydrographs shows that it is need to induce a significant first peak discharge a minimum amount of 200mm of rainfall.

Winter (dry) and spring (regular) seasons in this dry year result in low Runoff coefficient about 30% for LOU and SC, 2 times lower than for regular or wet years.

The two medium years recorded on average higher rainfall amounts for autumn than for winter with respectively 45% and 33% of the annual rainfall, correspond almost to 700mm of rainfall in 3 months. The percentage of Qs amount flowing during this season correspond to 36% of the annual total amount with a runoff coefficient of 30%, clearly very high value comparing within both dry and wet years. Despite a lower amount of rainfall during the winter period corresponding to about 500mm, the percentage of the annual Qt is higher than for autumn about 50% for LOU and 47% for SDC due to a large increase of the runoff coefficient attaining 56% for LOU and 65% for SDC. Spring was dry (only 16% of annual precipitation) with a similar percentage of Qt, corresponding to a decrease on runoff coefficient. During summer period despite very low rainfall amount, runoff coefficient remains high 30% for LOU and 50% for SDC.

Wet years present a general increase on winter rainfall amount attaining for the 3 study years an impressive average value of 1127mm representing half of the total annual rainfall amount and leading to about 60% of the annual Qt amount, with runoff coefficient attaining 70%. Spring recorded relatively high rainfall averaging about 600mm and runoff coefficient remain very elevated higher than 60%.

The summer period presents a normal rainfall amount, nevertheless runoff coefficient stays high, about 30 %.

TABLE 6A. *SEASONAL BEHAVIOR OF STREAMFLOW, FOR DRY (1), MEDIUM (2) AND WET YEARS (3).*

ALL YEARS	R	Rs/R	LOU Qt	Qs/Qt	Qt/R	R	Rs/R	SDC QT	Qs/Qt	Qt/R
	mm	%	mm	%	%	mm		mm		%
sep-oct-nov	3347	30	825	16	25	2893	30	647	14	22
dec-jan-feb	4596	41	2946	56	64	3878	40	2649	55	68
mar-apr-may	2760	24	1383	26	50	2395	25	1358	28	57
jun-jul-aug	581	5	126	2	22	533	5	132	3	25
Total	11284	100	5280	100		9698	100	4785	100	

DRY YEAR	R	Rs/R	LOU Qt	Qs/Qt	Qt/R	R	Rs/R	SDC QT	Qs/Qt	Qt/R
	mm	%	mm	%	%	mm		mm		%
sep-oct-nov	380	32	22	10	6	314	32	24	11	8
dec-jan-feb	189	16	56	27	29	156	16	55	25	35
mar-apr-may	499	42	129	62	26	412	42	131	60	32
jun-jul-aug	125	10	2	1	2	103	10	7	3	7
Total	1192	100	208	100		984	100	217		

MEDIUM YEAR	R	Rs/R	LOU Qt	Qs/Qt	Qt/R	R	Rs/R	SDC QT	Qs/Qt	Qt/R
	mm	%	mm	%	%	mm		mm		%
sep-oct-nov	1376	45	417	36	30	1184	45	391	33	33
dec-jan-feb	1027	33	579	50	56	861	33	556	47	65
mar-apr-may	495	16	146	12	29	425	16	202	17	48
jun-jul-aug	177	6	26	2	15	158	6	45	4	29
Total	3074	100	1168	100		2628	100	1194		

WET YEAR	R	Rs/R	LOU Qt	Qs/Qt	Qt/R	R	Rs/R	SDC QT	Qs/Qt	Qt/R
	mm	%	mm	%	%	mm		mm		%
sep-oct-nov	1592	23	386	10	24	1395	23	232	7	17
dec-jan-feb	3381	48	2312	59	68	2861	47	2039	60	71
mar-apr-may	1766	25	1108	28	63	1558	26	1025	30	66
jun-jul-aug	279	4	97	2	35	273	4	79	2	29
Total	7018	100	3903	100		6087	100	3375		

***Table 6b.** Seasonal behavior of Streamflow by study year.*

		sep-oct-nov			dec-jan-fev			mar-abr-mai			jun-jul-aou		
		Rs/R	Qs/Qt		Rs/R	Qs/Qt		Rs/R	Qs/Qt		Rs/R	Qs/Qt	
	R	%	%		%	%		%	%		%	%	
	mm		LOU	SDC		LOU	SDC		LOU	SDC		LOU	SDC
2010/2011	1256	34	14	11	42	77	72	17	7	17	7	1	0
2011/2012	984	32	10	11	16	27	25	42	62	60	10	1	3
2012/2013	1763	26	8	5	38	48	51	32	43	44	4	2	1
2013/2014	2121	21	9	7	52	66	66	20	22	23	7	3	3
2014/2015	1372	55	45	46	25	37	31	15	15	17	5	3	6
2015/2016	2127	22	12	8	50	61	62	26	24	28	2	2	3
		sep-oct-nov			dec-jan-fev			mar-abr-mai			jun-jul-aou		
	R	Rs	Qs/Rs		Rs	Qs/Rs		Rs	Qs/Rs		Rs	Qs/Rs	
	mm	mm	%		%	%		%	%		%	%	
			LOU	SDC		LOU	SDC		LOU	SDC		LOU	SDC
2010/2011	1256	427	10	12	524	44	63	218	10	36	87	3	2
2011/2012	984	314	6	8	156	29	35	412	26	32	103	2	7
2012/2013	1763	477	15	9	692	64	67	590	69	67	80	24	9
2013/2014	2121	449	27	20	1109	69	70	416	66	65	146	29	27
2014/2015	1372	757	43	45	337	76	66	207	51	60	70	33	62
2015/2016	2127	469	31	22	1060	70	75	552	54	65	46	70	72
correlation / Rs			0,86	0,92		0,59	0,78		0,60	0,48		-0,50	-0,52

4.3.3 Soil moisture influence

In general terms, surface (0-7cm) soil moisture content (SM) is higher for LOU than for SDC catchment. The average SM content during the 6 study years is 20% for LOU and 16.5% for SDC. Considering a daily soil moisture content data set, the difference between the minimum and maximum SM content is greater for LOU (1.7 vs 39.4% for SDC and 3.0 vs 52% for LOU). At the level of monthly data set, both sites follow the same pattern (3.2 vs 32.3% for SC and 4.7 vs 34.4% for LOU. The interquartile value is also higher for daily than for monthly data set respectively but sensibly equal between site (8.3% vs 13.8% for SDC and 9.1 vs 12.6 for LOU).

Soil moisture content pattern differs between years in function of rainfall amount and distribution, but systematically attain the lowers values in July, August and September. The higher values don't follow a such clear tendency, but in general January and February have the wettest average SM content of the year, followed by November, December and March.

Soil Moisture content is related to Rainfall amount and in particular with the 3 antecedent precipitation days, better than daily rainfall amount. The Pearson coefficient is almost the same for the 2 sites (about 0.55). The polynomial tendency curve presents a slightly better R^2 for LOU than for SDC (0.51 vs 0.43).

The influence of SM content on Q is weak, QT and SM content present a Pearson correlation coefficient of 0.57 for both site regarding the daily data set. Nevertheless, the correlation increase to 0.72 for LOU and 0.68 for SC considering the monthly data set of SM content. The BT amount presents an even better correlation with SM moisture with 0.75 for LOU and 0.72 for SC.
A better correlation exists between SM content and SC, with the Pearson correlation coefficient attain values of 0.81 for LOU and 0.71 for SC, indicating that Soil Moisture content has a higher influence on streamflow percentage than amount.
The LOU catchment present in absolute term a higher soil moisture content that SC, and also a higher amplitude of SM variation during the year, that can explain that streamflow behaviour is constantly better related with soil Moisture content than SC catchment.

4.3.4 Consequences of large-scale afforestation on the hydrological cycle

Eucalypt stands have the reputation for producing a very high ET rate. But in fact the ET demand of Eucalypt stand is lower than Pine stands (740mm vs 900mm).
ET amount stayed very stable during the 6 study years indicating that even if for dry year (less 30% of rainfall), the forest stand didn't suffer any water stress, this fact being confirming by any significant breakdown on eucalypt biomass production during driest years referred by Boulet et al. (2011).
A decrease in total rainfall amount in the ambit of climatic change, will lead to a important reduction of RC and water availability.

4.4. Discussion

The most surprizing aspect shown by the data is the evapotranspiration of the mature pine (*Pinus pinaster Aiton*). This is to our knowledge the only dataset for this specie, and shows a higher value when compared with the data for the mature *Eucalyptus globulus Labill* stands. This to some extent contradicts the idea commonly accepted in society and academia, on the *Eucalyptus globulus* water consumption. Furthermore, it to some extent contradicts the work of Ferreira (2009), although this author does not present information for mature pine stands, Comparing the two studies, it is evident the wider span of time that pine stands take to mature and therefore to reach the highest evapotranspiration rates (e.g. while the mature eucalyptus reach full evapotranspiration rates 7 or 8 years after plantation or cut and regrowth. The pine stands need at least 20 years to reach the same rates, and those are higher than for the eucalyptus stands.
Catchment runoff is closely correlated with the amount of rainfall, that explains more than 90% of the variation, with the eucalyptus catchment presenting higher runoff amounts than the pinus. Rainfall also justifies a high percentage of the variation shown by the evapotranspiration, as percentage of the rainfall, again with the eucalyptus attaining

higher values for lower rainfall amounts. This, again contradicts the common belief that eucalyptus requires higher amounts of water to grow than the pine stands.

In what concerns the potential impacts of climate change, the high evapotranspiration percentages shown by the dry years may pose an overwhelming problem to the recharge of aquifers and to the maintenance of stream and rivers ecological flows. In fact, the during dry periods, limited water availability becomes an important factor (Zhang et al., 1999).

The effect of the dry year presented similar trends for the two catchments. This concurs with other paired catchment studies on afforestation, where observed reductions in total streamflow values ranged from 41 to 69% depending on tree ages (8 to 21 years old) and reductions in the low flows reached 100%. (Fahey and Jackson, 1997, Brown et al., 2005, Lane et al., 2005).

4.5. Conclusions

The study area presents a large interannual variation in term of annual rainfall amount, with a prevalence of wet year during the study period. There is a predominance of winter rainfall (41%), followed by autumn rainfall (24%), spring (24%) and a very dry summer (5%).

In a general way, an increase on annual rainfall amount corresponds principally to a proportional increase in number of events per year and in total hours of rainfall rather than an increase in event duration or rainfall intensity.

The number of rainfall events > 60mm is relatively few (14%), but represent 43% of the annual precipitation amount. Half of annual total rainfall amount in concentrated in a few large and intense rainfall events.

The annual streamflow amount (Q) varies by a factor of 6.5 between years, LOU presenting a larger variation than SDC.

There is a very straight positive linear correlation between the annual rainfall amount (R) and the total streamflow amount (Q). SDC shows an even still better correlation than LOU. It is not the case for Runoff coefficient that present a poor correlation with annual rainfall amount for both catchments.

Annual ET amount is relatively constant through the six years of study and not influenced by the total rainfall amount. The average ET of LOU (907 mm) is higher than for SDC (739mm) indicating the importance of forest type, pine consuming much more water than eucalypt stands.

In term of separation of annual total streamflow (Q) between base flow (BT) and surface runoff (SR), BT represents 60% of Q for LOU and 52% of Q for SDC.

Considering the seasonal behaviour of Q in average for all the study years, only 15% of Q occurred during the autumn contrasting with the 30% of rainfall amount corresponding to Runoff Coefficient of 23%. It is during the winter, the wettest season (41% of the annual rainfall amount) that the streamflow response is the most important, half of the annual Q flowing during this period corresponding to a RC of about 67%

The seasonal behaviour of Q differs between type of year, but it is in autumn that seasonal RC is most influence by rainfall amount. In fact, a threshold of a minimum about 200mm depending of the kind of event is necessary to obtain a significant response in term of streamflow in autumn.

Dry year present then beside weak rainfall amount very low Runoff coefficient about half than for regular and wet years reflecting to a very low Q. The ET amount is constant over the six study years, a reduction in annual total rainfall amount lead to a large decrease in Q amount and not in ET, and RC will then decrease proportionally to the annual rainfall amount.

Normal years present a predominance of rainfall during autumn leading to a large increase of the RC during this season, nevertheless the autumn RC maintain lower than winter RC.

Wet years presented a predominance of precipitation during winter (half of the annual total amount), 60% of the Q, with very high RC of about 70%.

Soil moisture content is sensibly higher and with more important variations for LOU than for SDC and related better with 3 days API. Soil Moisture content and SC display a good correlation with an even better correlation for LOU, indicating that Soil moisture content influence the RC of the catchment.

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Chapter 5

Boulet, A.-K., Prats, S.A., Malvar, M.C., González-Pelayo, O., Coelho. C.O.A., Ferreira, A.J.D., Keizer, J.J, (2015) Surface and subsurface flow in eucalyptus plantations in north-central Portugal. *Journal of Hydrology and Hydromechanics*, 63(3): 193-200.

Doi: 10.1515/johh-2015-0015

Surface and subsurface flow generation processes in eucalyptus plantations in north-central Portugal

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Abstract
In the Baixo Vouga area located at the north-central region of Portugal, forests cover half of the territory, of which two thirds are Eucalypts plantations. The hydrological implications of this large-scale introduction of eucalypt are unknown. The aim of this exploratory study, performed at the Caramulo Mountains, is to describe overland flow (OLF), subsurface flow (SSF) and streamflow (SF) processes in a catchment dominated by Eucalyptus plantations. The main conclusions are that annual OLF rate is low, spatially heterogeneous between 0.1% and 5.75% and occurs mainly during the wet season as saturation excess, particularly as return flow. Hortonian OLF due to the strong soil water repellence (SWR) is dominant during the dry season. SSF is the dominant mechanism, it originates from matrix flow and pipe flow at the soil-bedrock interface, predominantly during the wet season under saturated conditions. Matrix flow is correlated with soil moisture content, with a threshold of 25 %. Pipe flow starts with saturation of the soil bottom, due to a large network of macropores, they can flow without saturation of the entire soil profile. Stream flow response is highly correlated with matrix flow behavior in timing and intensity. SWR induces a very patchy moistening of the soil, concentrates the fluxes and accelerates them almost 100 times greater than normal percolation of the water in the matrix.

Keywords
Overland flow; Subsurface flow; Streamflow; Soil moisture; Eucalypt forest

5.1. Introduction

In the Baixo Vouga region of north-central Portugal, forests now occupy almost half of the territory. Two thirds of these forests are plantations of Eucalyptus, which started to be introduced on a large scale in continental Portugal by the middle of the twentieth century and have since seen an effulgent expansion. The last, national forest inventory revealed that Eucalyptus had become the predominant tree species in Portugal, occupying 26% of the total forested area. Eucalyptus stands present a large economic interest, as the main raw material for paper pulp production, one of Portugal's leading industries.

The hydrological implications of this large-scale introduction of eucalypt monocultures plantation are currently being studied in a series of experimental headwater catchments, in the mountainous part of the Baixa Vouga region. The existing studies, however, have focused on overland flow generation and, to a lesser extent, runoff generation at the catchment scale but the linkage between both scales has received little research attention so far. Furthermore, measurement of subsurface flow has never been undertaken.

In forests, overland flow is widely considered to be an important hydrological pathway and is frequently cited as the principal stormflow generation process, resulting in a rapid response of the discharge hydrograph. While Hortonian-type overland flow is generally associated to regions with (semi-)arid climates (Albergel et al., 2003b) and to soils with much lower infiltration capacities than the forest soils in the study region, its potential importance in the streamflow response of the Caramulo headwater catchments cannot be discarded for various reasons. First, many Eucalyptus plantations in the study region are intensively managed with frequent use of machinery, and compaction of the soil surface is known to enhance Hortonian overland flow (Ziegler et al., 2001). Second, many Eucalyptus plantations in the Caramulo Mountains have a low ground cover of vegetation and litter and a high cover of stones, especially when they are recently planted, and Hortonian overland flow is often associated to areas with a sparse vegetation and/or a very stony soil surface (Ruiz-Sinoga et al., 2010). Third, the Eucalypt plantations in the study region are well-known for their strong to extreme soil water repellency, especially after dry spells (Doerr et al., 2000; Keizer et al., 2005a; Santos et al., 2013), and soil water repellency is widely regarded to induce Hortonion overland flow (Ferreira et al., 2000; Keizer et al., 2005b; Leighton-Boyce et al., 2005).

Also saturation-excess overland flow can be expected to play an important role in streamflow generation in the study region, especially during the wet winter seasons when soil water repellency tends to be less pronounced (Doerr et al., 2000; Keizer et al., 2005a). Namely, rainfall is rather high in the upper Caramulo Mountains in particular, amounting to over 1400 mm per year, and soils tend to be shallow (Malvar et al., 2013; Shakesby et al., 1996). Bonell and Gilmour (1978), for example, found widespread saturation overland flow generation when high intensity rainfall combined with a perched water table due to the presence of an impermeable layer at shallow depth. Subsurface flow can equally be expected to contribute markedly to stream flow generation in the study region, due to the elevated rainfall and the steep slopes in the experimental headwater catchments.

According, for example, to Weiler et al. (2006), subsurface flow can represent a significant mechanism of stormflow generation in humid environments on steep hillslopes. Two types of subsurface flow are usually identified, i.e. lateral matrix flow and macro-pore/pipe flow.

Lateral matrix flow occurs in general on steep slopes with soils that have a high infiltration capacity and, at the same time, are shallow or have an impermeable or poorly permeable soil layer at limited depth.

The behavior of lateral matrix flow has been found to depend on soil depth (Hopp and McDonnell, 2009), soil porosity (Weiler and McDonnell, 2004), bedrock micro-topography (Tromp van Merveeld and McDonnell, 2005). Sidle et al. (2000) found that preferential subsurface flow through macro-pores and/or pipes contributed in an important manner to runoff generation. Especially macropore flow could be important in the study region, as Eucalyptus trees develop extensive root networks during successive rotation cycles, re-sprouting vigorously after logging. Furthermore, preferential flow could be an important mechanism of infiltration under repellent soil conditions (Kramers et al., 2005; Santos et al., 2013).

The main aim of this exploratory study was to describe overland flow, subsurface flow and stream flow processes in a catchment dominated by Eucalyptus plantations, and, more specifically, to identify if these processes various through time and, in particular, with contrasting antecedent soil moisture conditions.

5.2. Materials and Metodos

5.2.1. Study area

The present study was carried out in the foothills of the Caramulo Mountains of north-central Portugal (Figure 1). The area is mainly covered by forests and, in particular, Eucalyptus plantations, which now constitute a mosaic of stands in different rotation cycles. The prevalent Eucalypt species is *Eucalyptus globulus* Labill, which is a fast growing tree species that re-sprouts vigorously from multiple stems after logging. In the region, an Eucalyptus plantation typically involves three rotation cycles of 10-12 years, after which a new plantation is established, in general following the removal of the existing root systems and ground operations such as rip-ploughing and bench terracing.

The climate of the study area is temperate with wet winters and dry summers, and can be classified as Csb according to the Köppen's system (DRA_Centro, 1998). The mean annual temperature varies between 12.5 and 15.0 ºC, while mean annual precipitation varies between 1400 and 1600mm (Atlas do Ambiente, Agência Portuguesa do Ambiente, 2001).

The Caramulo Mountains are part of the Hesperian Massif, which is dominated by Pre-Ordovician metamorphic sediments of the schist and greywackes complex. Slopes are typically very steep (>20 degrees), and soils are stony, weakly-structured and shallow. The soils of the study area are mapped – at a scale of 1:1,000,000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al.,1971, 1973).

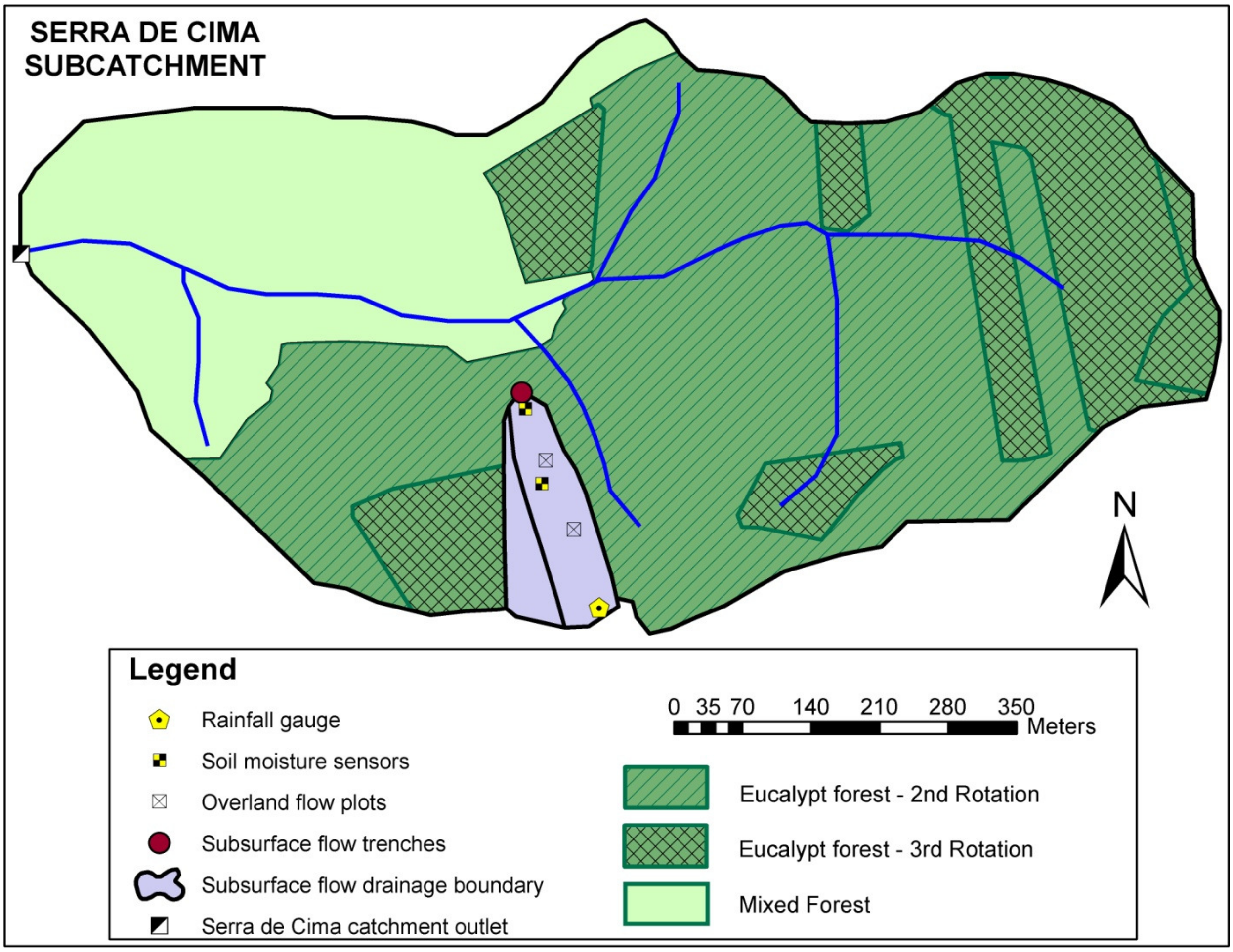

FIGURE 1. *LOCATION OF STUDY AREA AND STUDY SITE IN THE ALFUSQUEIRO RIVER BASIN, NORTH-CENTRAL PORTUGAL, AS WELL AS LAND COVER AND EXPERIMENTAL SET-UP IN SERRA DE CIMA HEADWATER CATCHMENT.*

5.2.2. Study site and experimental design

This study was carried out in a small, 52 ha headwater catchment of Alfusqueiro River Basin (Figure 1). This so-called Serra de Cima experimental catchment is located between 273 and 485 m a.s.l., has steep slopes of, on average, 16 º, and is covered for some 70 % by mono-specific plantations of *Eucalyptus globulus* Labill. and for the remaining 30 % by a mixed forest of eucalypt, maritime pine and acacias.

During the study period, the Serra de Cima catchment was instrumented with a hydrometric station, three runoff plots and 3 trenches for measuring subsurface flow (Figure 1). The latter had been installed for the specific purpose of this study, whereas the hydrometric station and the runoff plots had been installed several years before. Rainfall was measured using a tipping-bucket rainfall gauge with a 0.2 mm resolution (Pronamic RAIN-O-MATIC Professional) linked to an ONSET event data logger that was installed in the Serra de Cima village, at roughly 1 km distance, and a storage rainfall gauge that was installed in an open area next to the runoff plots.

The hydrometric station consisted of a H-flume, where the water level was recorded at 2-minute intervals using a pressure sensor (Campbell Scientific CS450) linked to a data logger (Campbell Scientific CR200.

The three runoff plots and the subsurface plot were installed at an Eucalypt plantation in the second rotation cycle, which had been logged for the first time in 2002. In 2012, the density of Eucalyptus amounted to 970 trees.ha^{-1} and 1857 trunks.ha^{-1}, its total basal area to 16 m^2.ha^{-1}, and its height to roughly 12 m. The stand's understory was then dominated by broom (*Pterospartum tridentatum*), heather (*Erica spp.)* and gorse (*Ulex spp.* and *Genista spp.),* providing an almost complete soil cover and reaching heights of 80-100 cm. The stand's litter layer also provided an almost complete soil cover and was typically some 10 cm thick, comprising an F-horizon of Eucalyptus bark, branches and decomposing leaves as well as an O-horizon. The plantation was located on a convex-linear hillslope, with a slope angle that ranged from3º at the top till 27º at the bottom. The soils of the plantation varied between Humic Regosols on the convergent slope parts and Humic Leptosols on the remaining parts, with soil depths ranging from 20 to 80 cm. The soils are very stony with stone fractions of roughly 50% in the topsoil, probably reflecting past ground operations. Soil texture is silt loam, with the silt fraction amounting to roughly 60 % and the sand and clay fractions to 20 %. The topsoil is rich in organic matter, typically exceeding 10 %.

The three runoff plots were located in the upper, middle and lower part of the study slope to assess overland flow generation across the slope. The plots were 2 m wide by 8 m long, and were bounded by aflexible brass strip of about 20 cm height. The outlet of the runoff plots consisted of a wash trap (with a filter to retain coarse elements) that was connected with a garden hose to diverge the runoff to a tipping-bucket device and, ultimately, to collect it in a 70 L tank. The tipping-bucket devices consisted of two bascule buckets with a capacity of 0.5 L, whose movement was registered by an analogue counter and, in two of the three cases, by an ONSET event data logger as well. The counts of analogue counters were verified at 1- to 2-weekly intervals, depending on rainfall. During these fieldtrips, also the runoff in the tanks and the rainfall in the storage rainfall gauge were measured. Next to the middle runoff plot, four soil moisture sensors (Decagon EC-5) connected to a data logger (Decagon Em5b) were installed, divided in two sets (a and b) located at some five meter distance from each other and each set comprising a sensor installed at 2.5 cm soil depth and a sensor installed at 7.5 cm soil depth (SM 2.5cm and SM 7.5cm). The soil moisture readings were recorded at 15 min intervals.

The second measurement site is situated near the subsurface trenches. Soil moisture is recorded more deeply: 4 probes were inserted vertically throughout the soil profile at 20cm, 40cm, 60 and 80cm depth (SM 20cm, SM 40cm, SM 60cm and SM 80cm).

The subsurface plot was installed at the bottom of the Eucalyptus plantation, about 80 m upslope of the channel. It consisted of three trenches of 3 meter wide and 1 meter high that were excavated down to the bedrock. This was done on the upslope side of a forest trail to facilitate excavation of the soil profile as well as of the open channels at the base of the trenches that routed the subsurface flow plus incident rainfall. The water produced by each trench was first routed to a storage tank and then, using garden hose, to a tipping-bucket gauge equipped with an ONSET event data logger. Subsurface flow was estimated by subtracting the precipitation recorded by the automatic rainfall gauge. The trenches were estimated to drain a convergent slope area of about 1.9 ha. Field observations during rainfall events revealed that the central trench included seven macro-pores with a diameter of 3-8 cm that were situated just above the soil-bedrock interface as well as several smaller macro-pores situated some 40 above this interface. The two lateral trenches, however, did not reveal any macro-pores. Hence, the central trench was inferred to produce subsurface flow principally by pipe flow and the two lateral trenches exclusively by matrix flow. Accordingly, the central trench will be referred to underneath as “SSF Pipe” and the lateral trenches as “SSF Matrix 1” and “SFF Matrix 2”.

5.2.3. Data collection and analysis.

The data used in this study were collected during the 2013/14 hydrological year, starting on 1 of October 2013 and ending on 30 of September 2014. The data was analyzed at a temporal resolution of one hour. While rainfall, overland flow and stream flow were analyzed in mm h-1, subsurface flow was expressed in L.h-1. This was done because no information was available on bedrock topography and, at the same time, because a Digital Terrain Model (DTM) would provide an unreliable estimate of the subsurface drainage area (Freer et al., 2002). Subsurface flow was analyzed separately for the individual trenches, though, as appointed by Woods et al. (1996) a large variation in flow rates between adjacent troughs difficult an accurately estimating subsurface flow at the hillslope scale.

5.3. Results

In this study, a total of five rainfall-runoff events that occurred during the hydrological year 2013/14 were selected to demonstrate differences in soil wetting and runoff response under dry, intermediate and wet antecedent soil moisture conditions. An overview of these events is given in Table 1 and a detailed description of their main features is presented in the next sections. The reason to include three subsequent “dry” events rather than a single one had to do with the fact that their sequence illustrated well the wetting-up of the soil after a dry spell, with antecedent topsoil moisture contents increasing gradually from the first till the third event. In fact, the antecedent topsoil moisture contents of the third "dry" event differed little from those of the "intermediate" event (17-28 vs. 20-30 %) but the moisture contents at greater soil depth did show a marked contrast between the "dry" and "intermediate" events (6-20 vs. 10-25 %). This initial wetting-up process occurred relatively late in the year, as November 2013 was much drier than on average (70 vs. 172 mm). Also the "wet" event analyzed here occurred under somewhat exceptional conditions, as January and February 2014 were much rainier than on average (442 vs. 174 mm, and 360 mm vs. 119 mm, respectively). (Figure 2)

CHAPTER 5

TABLE 1. SUMMARY OF THE MAIN CHARACTERISTICS OF FIVE SELECTED RAINFALL-RUNOFF EVENTS IN A MONO-SPECIFIC EUCALYPT PLANTATION AND A EUCALYPT-DOMINATED CATCHMENT.

		EVENTS				
		Dry SM antecedent			Intermediate SM antecedent	Wet SM antecedent
		13-12-2013	17-12-2013	19-12-2013	24-12-2013	09-02-2014
total rainfall amount per event (mm)		18	14	60	95	34
hourly rainfall peak (mm.h-1)		4	5	12	16	6
SM antecedent (%) (top soil < 10cm deep)	max	13	20	28	29	45
	min	6	13	19	20	23
SM antecedent (%) (>20cm deep)	max	14	15	17	24	33
	min	6	6	6	10	12
overland flow peak (mm.h^{-1})	0.0016 há	0.015	0.008	0.060	15.000	0.008
overall runoff coeff (%)		0.15	0.18	0.46	28.70	0.12
subsurface flow peak SSF (l.h^{-1})	1.92 há	0	0	860	1076	780
total SSF 3 trenches (Lat1, Lat2, Central)				3512/2582/0	8680/4870/8513	2773/?/3189
SSF per unit of rainfall (l.mm^{-1} rainfall)				102	232	> 216
streamflow peak (mmh-1)	52 há	base	base	0.7	6.0	1.0
peakflow (% incident rainfall)				18.2	55.9	23.1

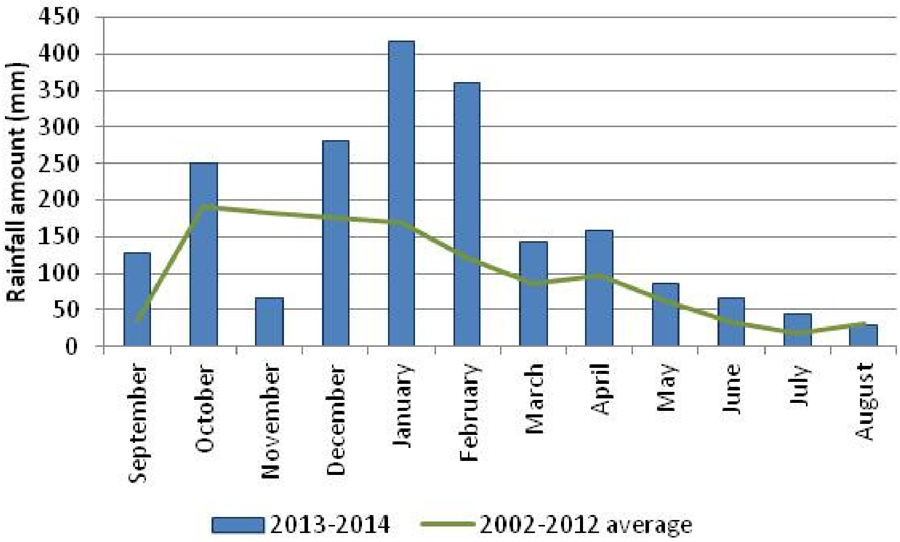

FIGURE 2. *RAINFALL CHARACTERISTICS – MONTHLY RAINFALL AMOUNT IN MM OF THE HYDROLOGICAL YEAR 2013-2014 COMPARED WITH MEDIAN OF MONTHLY RAINFALL AMOUNT FROM 2002 TO 2012.*

5.3.1. Three Successive Rainfall-Runoff Events under Dry Antecedent soil moisture conditions

The first two rainfall events with "dry" antecedent soil moisture conditions were relatively minor compared to the third one, both in terms of total amount (15-20 vs. 60 mm) and maximum hourly intensity (4-5 vs. 12 mm h-1) (Table 1; Figure 3). Nonetheless, the three rainfall events produced similar responses in terms of topsoil wetting, with three of the four sensors below 10 cm depth revealing marked increases in soil moisture contents to similar maximum values in the three instances (even though these maximum values differed between the three sensors). The fourth sensor revealed a rather distinct response, both compared to the other sensors as among the three events. Soil wetting at 7.5 cm depth at point b was clearly slower than at the other measurement points in all three events and, at the same time, was markedly less pronounced during the first two events than during the third one, with maximum values of 17-21 vs. 47%.

The largest and most intense event produced a stronger overland flow response than the two preceding events. Nonetheless, the overall runoff coefficients of the three events were similarly small (0.14, 0.18 and 0.46% respectively). Hourly overland flow amounts attained higher peak values during the third when compared to the first two events (0.06 vs. 0.01-0.02 $mm.h^{-1}$) but, within events, their variation followed closely the temporal pattern in rainfall intensity.

The four soil moisture sensors at greater soil depth linked to the subsurface runoff plot showed a response along the three rainfall events that was consistent with that of the sensor at 7.5 cm depth at measurement point b. They revealed subsequently: (i) a lack of response during the first event; (ii) minor increases during the second event at the upper depths (20-40 cm) but not at the lower depths (60-80 cm); and (iii) generalized increases during the third event but more pronounced at the upper than lower depths.

The pattern in subsurface flow along the series of three rainfall events bore definite resemblance to that in overland flow. The third event produced noticeable amounts of subsurface flow, with peak values of 400-500 $L.h^{-1}$, while the preceding two events did not. The observed subsurface flow originated exclusively from the two lateral trenches and, as mentioned in section 2, was interpreted to correspond to matrix flow. The matrix flow hydrographs of the two trenches were largely coincident. Furthermore, their rising limbs closely followed the soil wetting pattern at 20 and 40 cm depth, whereas their ends lagged some ten hours behind the end of the rainfall.
Similar to subsurface flow, stream flow did not reveal any response to the first two events, while it did to the third event. Also, the rising limb of the stream flow hydrograph of this third event closely matched the rising limps of its matrix flow hydrographs. The stream flow response started ten hours after the beginning of the rainfall event, while peak flow lagged 3 hours behind the maximum hourly rainfall intensity. The overall runoff coefficient at the catchment scale was markedly higher than that of the overland flow plots (18.2 vs. < 1 %).

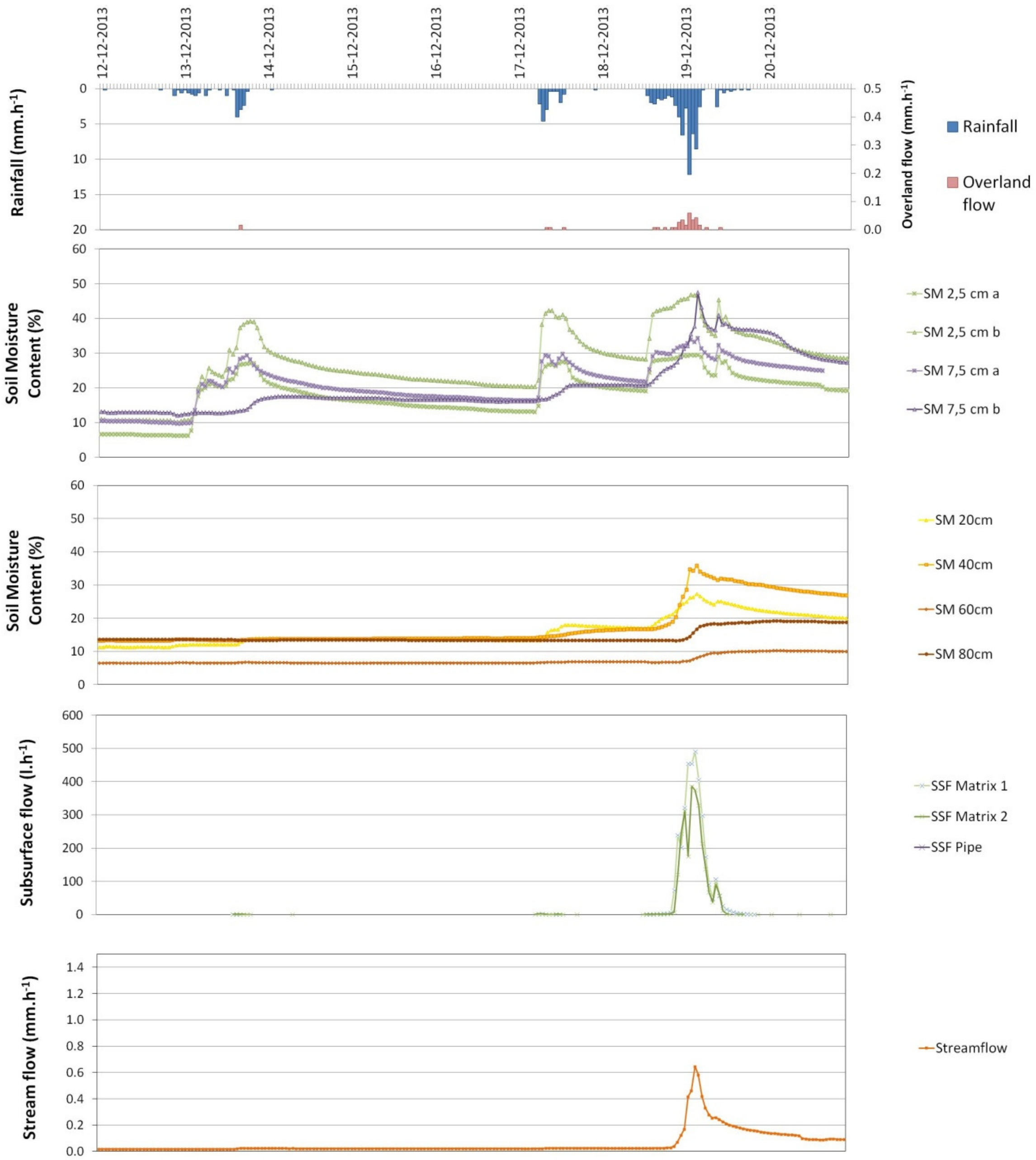

FIGURE 3. *RAINFALL, MOISTURE CONTENT AT DIFFERENT SOIL DEPTHS, AND OVERLAND, SUBSURFACE AND STREAM FLOW FOR THREE SELECTED EVENTS WITH DRY ANTECEDENT SOIL MOISTURE CONDITIONS IN A MONO-SPECIFIC EUCALYPT PLANTATION AND A EUCALYPT-DOMINATED CATCHMENT.*

5.3.2. A Rainfall-Runoff Event with Intermediate antecedent soil Moisture conditions

The rainfall event with “intermediate” antecedent soil moisture conditions occurred five days after the third “dry” event, on December 24 2013, and involved the largest rainfall amount (95 mm) and the highest rainfall intensity (16 $mm.h^{-1}$) of all five events analysed in this study (Table 1; Figure 4). The event produced a similar pattern of topsoil wetting as the third “dry” event, as the changes in soil moisture contents agreed well among the three operational sensors below 10 cm soil depth (i.e. including the sensor at 75 cm depth at point b, which had shown deviant behavior during the first two dry events). Also the differences between the sensors in terms of their minimum as well as maximum recorded values were in line with the findings for the third "dry" event.

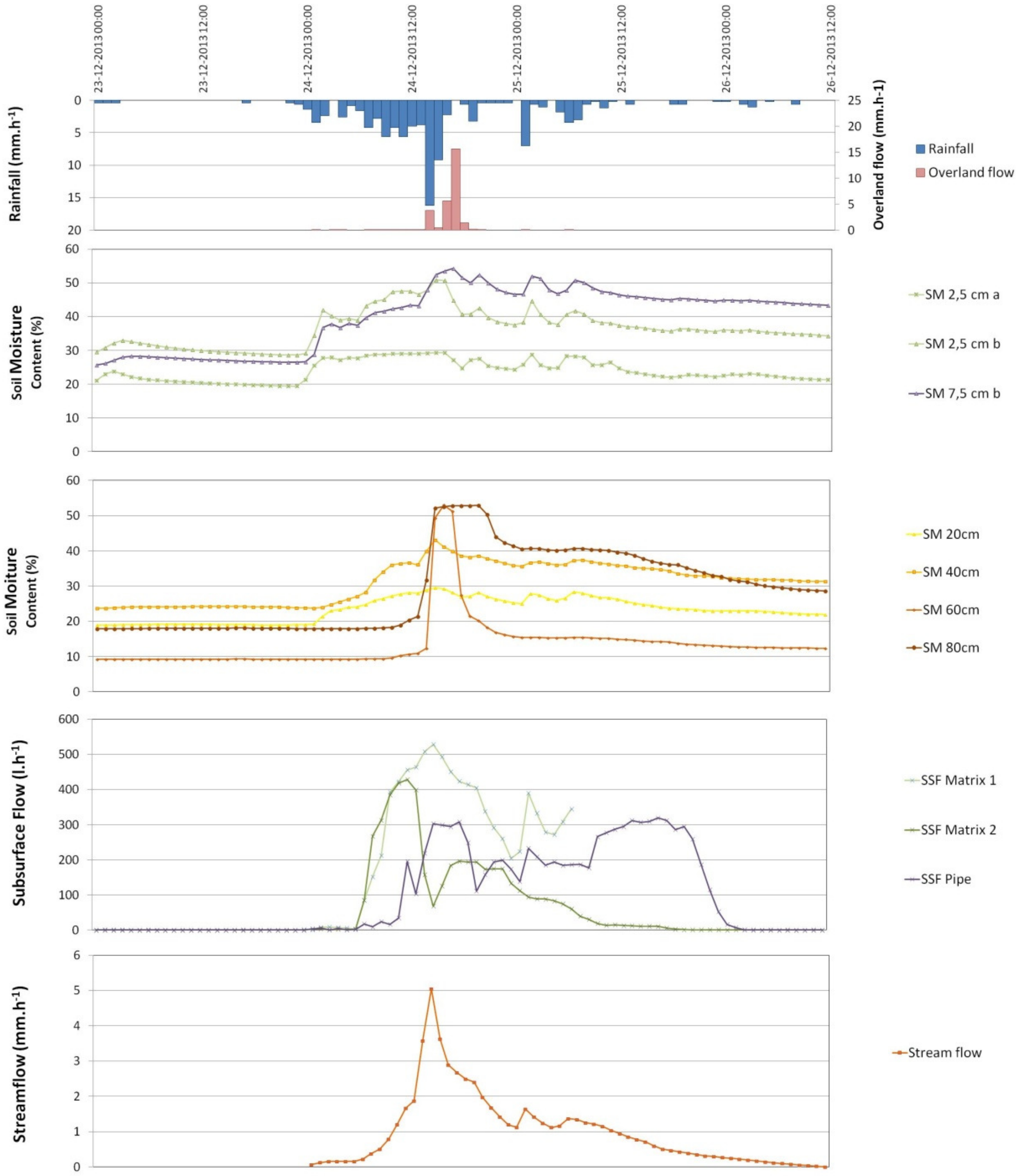

FIGURE 4. *RAINFALL, MOISTURE CONTENT AT DIFFERENT SOIL DEPTHS, AND OVERLAND, SUBSURFACE AND STREAM FLOW FOR A SELECTED EVENT WITH INTERMEDIATE ANTECEDENT SOIL MOISTURE CONDITIONS IN A MONO-SPECIFIC EUCALYPT PLANTATION AND A EUCALYPT-DOMINATED CATCHMENT.*

In what concerns the overland flow generation during the "intermediate" event, the bulk of this overland flow was produced during a relatively short period of five hours, with one clear peak in overland flow of 15 mm.h-1. Quite remarkably, this peak occurred during a

spell without rainfall and three hours after the - also pronounced - peak in rainfall. Furthermore, this overland flow peak occurred when topsoil moisture values of two of the three operational sensors had already dropped below their maximum.
The four soil moisture sensors linked to the subsurface runoff plot behaved in a similar manner during the first part of the “intermediate” event as they had done during the third “dry” event, with a marked response by the upper two sensors (20-40 cm) as opposed to no response by the lower two sensors (60-80 cm). During a second part of the event, however, the soil moisture contents at 60 and 80 cm depth increased very sharply and to maximum values well above those at 20 and 40 cm depth (52 vs. 29-43 %). These maximum values were attained simultaneously at the two lower depths - 1 hour after the rainfall peak – but were maintained for a considerably shorter period at 60 than 80 cm depth (3 vs. 6 hours). The suggested drainage at 60 cm depth was also exceptionally fast when compared to that at 20 and 40 cm depth.

The subsurface flow response of the “intermediate” event agreed with that of the third “dry” event in various aspects: (i) significant flow was produced at an earlier stage by the lateral trenches than by the central trench or, in other words, significant matrix flow preceded significant macro-pore flow; (ii) the flow from the lateral trenches started before soil moisture at 20 and 40 cm depth reached its maximum as well as before soil moisture at 60 and 80 cm depth started to increase; (iii) the peak flows of the two lateral trenches, differing roughly 100 $L.h^{-1}$ in both events. The central trench produced substantial amounts of subsurface flow (200 $L.h^{-1}$) before soil moisture contents at 60 and 80 cm even started to increase markedly but did not produce peak values till soil moisture contents at these depths reached their maximum values. These peak flows of around 300 $L.h^{-1}$ continued to occur for more than 24 hours, although with some fluctuations that were not easily understood. By contrast, subsurface flow from the lateral trenches was closely associated to soil moisture contents at 40 cm depth (Figure 5).

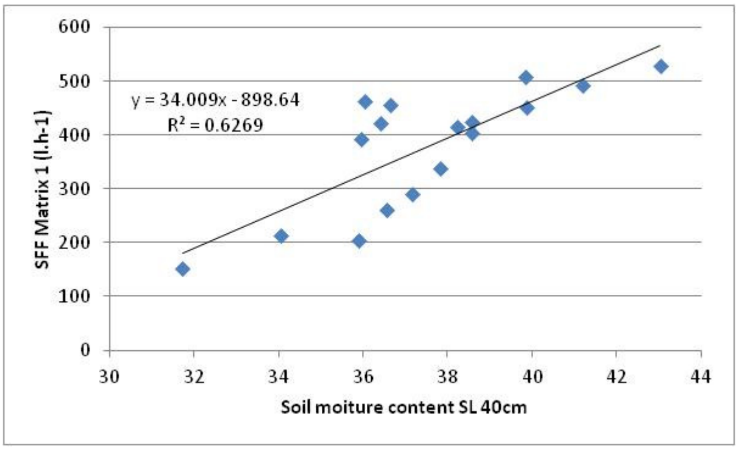

FIGURE 5. RELATIONSHIP OF SUBSURFACE FLOW FROM THE LATERAL TRENCH 1 WITH SOIL MOISTURE CONTENT AT 40 CM DEPTH FOR THE RAINFALL-RUNOFF EVENT WITH "INTERMEDIATE" ANTECEDENT SOIL MOISTURE CONDITIONS.

Like overland flow response, stream flow response to the "intermediate" event was much more pronounced than that of the third "dry" event, with an overall runoff coefficient of 55.9 % as opposed to 18.2 % and a peak stream flow of 6 mm h-1 as opposed to less than 0.7 mm.h^{-1}. This catchment-scale runoff coefficient thus also clearly exceeded the above-mentioned plot-scale runoff coefficient of 27.2 %, as was the case for the third "dry" event. A further correspondence with this third "dry" event was the agreement between the rising limbs of the hydrographs of stream and subsurface flow. This agreement was most pronounced in the case of the matrix flow from lateral trench 1 and extended to the falling limbs of the hydrographs, as shown in Figure 6. The peak in stream flow clearly preceded the peak in overland flow in the case of the "intermediate" event, unlike in the case of the third "dry" event. This difference in peak timings amounted to as much as 2 hours.

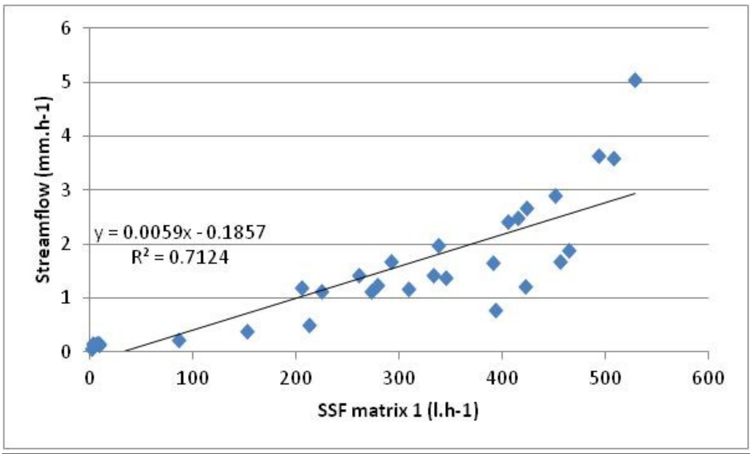

FIGURE 6. RELATIONSHIP OF STREAM FLOW WITH SUBSURFACE FLOW FROM LATERAL TRENCH 1 FOR THE RAINFALL-RUNOFF EVENT WITH "INTERMEDIATE" ANTECEDENT SOIL MOISTURE CONDITIONS.

5.3.3. A Rainfall-Runoff Event with Wet Antecedent Soil Moisture Conditions

The selected rainfall event with “wet” antecedent soil moisture conditions occurred at the beginning of February 2014, after an exceptionally rainy January month as was referred earlier (Table 1; Figure 7). The event itself was a relatively minor and low-intensity storm, with both, rainfall total (34 mm) and maximum intensity (6 $mm.h^{-1}$) accounting to roughly half the figures of the third “dry” event. Unlike any of the other five events, it produced no major variations in topsoil moisture contents. Throughout this event, moisture contents were at or close to the maximum values recorded during this study, with clear differences between the individual soil moisture sensors that agreed well with their differences in the other events.

The “wet” event produced as little overland flow as the two initial “dry” events (0.1 %) and with an equally low peak value as the two initial “dry” events (0.01 $mm.h^{-1}$). Overland flow generation did not seem to occur in a concentrated but in a dispersed way, as was also suggested by the second “dry” event. This could, at least in part, reflect the discrete nature of the recordings, inherent to tipping-bucket devices.

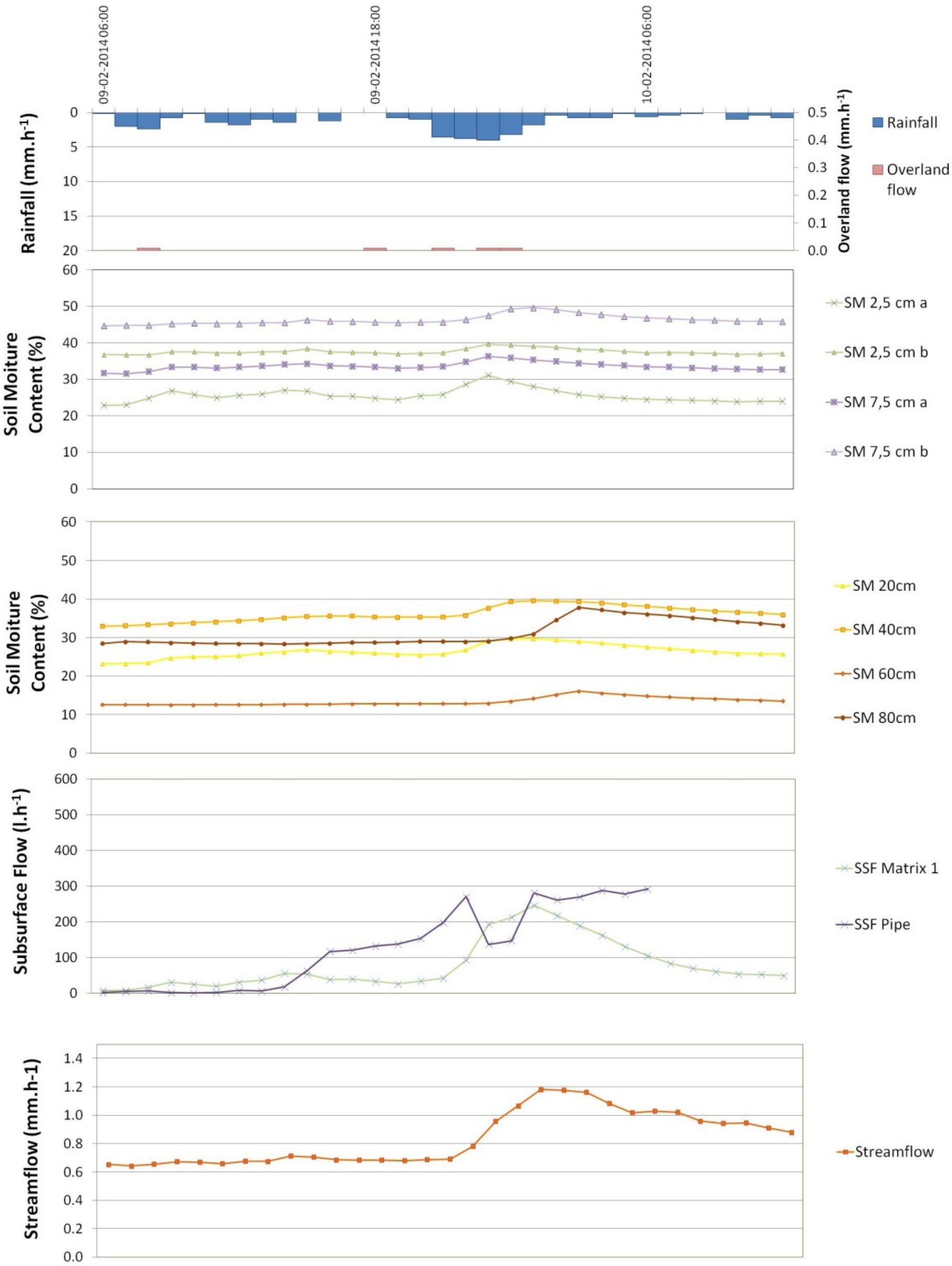

FIGURE 7. *RAINFALL, MOISTURE CONTENT AT DIFFERENT SOIL DEPTHS, AND OVERLAND, SUBSURFACE AND STREAM FLOW FOR A SELECTED EVENT WITH WET ANTECEDENT SOIL MOISTURE CONDITIONS IN A MONO-SPECIFIC EUCALYPT PLANTATION AND A EUCALYPT-DOMINATED CATCHMENT.*

The moisture sensors at greater soil depth revealed basically the same, lack of response as the topsoil sensors. Nevertheless, marked contrast existed between the soil moisture contents at 20 and 40 cm depth and those at 60 and 80 cm depth. While the former closely corresponded to the maximum values recorded in the various events (as was the case below 10 cm depth), the latter did not, remaining well below the peak figures of over 50 % attained during the “intermediate” event.

The subsurface flow response to the “wet” rainfall event resembled that of the “intermediate” rainfall event during the initial phase but subsequently diverged from it. During this initial 6-hour period, lateral trench 1 (the tipping-bucket device of lateral trench 2 was malfunctioning) responded more strongly than the central trench; afterwards, macro-pore flow tended to clearly exceed matrix flow. A further contrast with the “intermediate” event was related with the peak subsurface flow values produced by the two trenches. The peak value by the central trench was basically the same for both events (c. 300 $L.h^{-1}$), while the peak value by the lateral trench was roughly half of the values recorded for the “wet” when compared with the “intermediate event (500 vs. 250 $L.h^{-1}$). Unfortunately, technical limitations (of the tipping-bucket devices) did not allow estimating the total volumes of subsurface flows in all instances, thereby hampering a detailed comparison of the flow rates per mm of rainfall.

The “wet” event produced a similar increase in stream flow as the third “dry” event, amounting to a difference of about 0.6 mm h-1 between base flow and peak flow. Base flow was clearly higher at the start of the “wet” event than of any of the other events (0.6 $mm.h^{-1}$ vs. ≤ 0.1 $mm.h^{-1}$), confirming the overall wetness of the study catchment and, thereby, justifying the distinction from the other events. Overall runoff coefficient was about 23%, half of the value recorded for the “intermediate” event. The hydrographs’ rising limbs of the of stream flow and the subsurface flow from lateral trench 1 agreed remarkably well, similar to what was observed earlier for the third “dry” event as well as for the “intermediate” event. As such, this increase in stream flow lagged somewhat behind the period of highest rainfall intensities at the end of 9 February 2014.

5.4. Discussion

5.4.1. Overland flow

Overland flow generation in eucalypt plantations are expected to involve not only saturation-excess but also Hortonion processes, due to the association of eucalypts with strong to extreme soil water repellency (Ferreira et al, 2000; Keizer et al., 2005b; Leighton-Boyce et al., 2005). Ferreira et al. (2000), for example, found a negative correlation between the overland flow response of eucalypt plantations and antecedent soil moisture during the summer, and inferred that repellency-induced hortonian overland flow was the dominant process.

Following dry spells, low-intensity rainfall events are frequently observed to produce small amounts of overland flow in the study area, as was well-illustrated by the first two “dry” events included the present study. The minor amounts of observed overland flow were probably due to re-infiltration in wettable areas and, in particular, in areas with high infiltration capacity due to the presence of preferential flow paths, including macro-pores. The heterogeneous nature of spatial repellency patterns in eucalypt plantations during wetting and drying periods is well-established (Keizer et al., 2005a; Leighton-Boyce, 2005; Santos et al., 2013). Likewise, the occurrence of preferential flow in repellent soils is widely accepted (Doerr et al., 2000; Ritsema et al, 2005; Malvar et al., 2013). In agreement with Gomi et al. (2008), overland flow was highly localized during the first two “dry” events, with two out of three runoff plots producing no runoff.

During the rainy season, Hortonian overland flow might happen under exceptional circumstances under extreme rainfall intensity. During the “intermediate” event, a 15-minute peak in rainfall intensity of 34 mm h-1 produced an instantaneous runoff coefficient of 47 % at one of the runoff plots, while topsoil moisture contents were still below their maximum values. However, Boulet et al. (2007) estimated infiltration capacity in nearby soils to be about 30 mm h-1, so that the high runoff coefficient might involve a combination of Hortonian and saturation-excess overland flow, especially in the light of the high spatial variability in key soil properties. This spatial heterogeneity is well-demonstrated by the fact that the other two runoff plots produced hardly any overland flow during this peak rainfall intensity.
The “intermediate event selected or this study is a good example of overland flow generation by saturation excess. Two kinds of saturation excess overland flow seemed to be involved, i.e. saturation resulting from infiltration of rainfall and from lateral flow. The clear peak in overland flow that occurred after the rainfall had stopped suggested that the second mechanism was the main source of the measured runoff. This return flow mechanism could result from the highly irregular topography of the bedrock observed in the subsurface trenches, so that especially abrupt differences in soil depth would lead to exfiltration of subsurface flow. Sidle et al. (2000) demonstrated that return flow was controlled by soil depth as well as hillslope position within the catchment. In the present case, the importance of hillslope position in return flow was suggested by the fact that only the lowermost of the three runoff plots revealed a post-rainfall peak in overland flow.

5.4.2. Subsurface and streamflow

While the measurement of subsurface flow proved to be a challenge, also because flow volumes were much higher than expected, it provided valuable first insights into the hydrology of the study site as well as the experimental catchment. A key issue was the complexity of the subsurface runoff response, with marked variations between the selected rainfall-runoff events and, within the events, in time and space. Worth mentioning with respect to spatial variability was the importance of direct observation of subsurface flow in the field, revealing the - unsuspected - presence of various and variably-sized macro-pores and their heterogeneous distribution over the soil profile.

Subsurface flow is originated both by matrix flow and pipe flow at the soil-bedrock interface, produced mainly during the wet season by matrix flow and exclusively during the wet season for pipe flow. Matrix flow is correlated with soil moisture content of SM 40cm and not with threshold rainfall amount as demonstrated by Tromp-van Meerveld and McDonnell (2006) that demonstrated a clear threshold response of hillslope subsurface flow generation with storm total precipitation (55mm of rainfall). A threshold of 25% of soil moisture for SM 40cm is needed to start matrix flow, and saturation of the soil matrix is not a requirement. The matrix SSF discharge follows the behavior of SM 40cm moistening, increasing slowly as function of soil moisture content. As SM 40cm starts to drain, the matrix SSF discharge declines and remains active until the SM content attains a steady state of moisture. Matrix SSF discharge is also closely correlated with the stream flow discharge, both in terms of timing and intensity.

Pipe flow doesn't occur for dry soil moisture antecedent conditions, even for a large intense rainfall event of 60mm. For intermediate soil moisture antecedent conditions, initiation of pipe SSF is delayed relatively to the matrix subsurface flow (about 6 hours for the event of 24 of December 2013). It starts with the saturation of soil bottom, that happens in only half an hour due to a large network of macropores and doesn't require the saturation of the entire soil profile. Pipe flow attains the maximum discharge as both SM 60cm and SM 80cm become saturated. Observations in the field show an initial discharge produced by the large macropores located at the soil bedrock interface. The increase of the discharge is produced by the activation of smaller macropores located higher in the soil profile. This confirms than the activation of the pipes is related with the rise of the water table. Pipe SFF flow remains active after the end of the rainfall event for up to 24h. Pipe flow discharge is quite stable, but sensitive to new rainfall input, as report by Uchida et al. (2005) that determined that maximum pipe flow rate was sensitive to the measured rainfall intensity. Nevertheless, pipe SSF suffers only slight increases on discharge flow with a delay of one hour to rainfall. Pipe SFF switches off completely suddenly in less than 4 hours when SM content of SM 80cm reach 30%. Pipe SFF discharge behavior is not directly correlated with soil moisture content at the soil bottom. The saturation of bottom layer is needed to start SSF for medium soil moisture antecedent conditions, nevertheless as the network of pipes are preliminary activated, it seems that the network stays connected for soils close to the steady state. Then a moderate new input of rainfall leads to the re-start of pipe SSF without requiring saturation of the soil bottom.

5.4.3. Soil wetting

For dry soil moisture antecedents with severe SWR characteristics, rainfall infiltration pattern is driven by soil repellence characteristics. SWR is severe but patchy and strongly dichotomously distributed (Leighton Boyce, 2005) which leads to water infiltration in some restricted areas, as cracks, stones surface, roots, macropores. Due to the low soil moisture content of the soil surface, this network of preferential ways is nonetheless not connected, and water that travel through these pathways is quickly reabsorbed by the soil matrix.

With the progressive soil matrix moistening, SWR severity at soil surface is reduced and soil moisture infiltration pattern become more homogeneous. A threshold between 19% and 23% of soil moisture content was indicated by Santos et al. (2012) and Leighton Boyce et al. (2005), for wettable soil. The data don't allow to determine a threshold of soil moisture for wettable soil, but it indicates a delay in moistening for SWR area at SM 7.5cm b. After 60mm of rainfall amount, the repellence is totally broken and SM 7.5cm b reaches saturation state. Even after drying, this area never presents repellence characteristics again during the winter.

Water infiltration for the deeper layers follows a different behavior. For dry soil moisture antecedents, moistening of SM 20cm starts slowly, but as SM 20cm attains the threshold of 22%, the moistening of SM 40cm becomes much faster than the moistening of SM 20cm. This could mean that water starts to travel through preferential paths efficiently. As the matrix moisture of SM 20cm attains a determined threshold level, soil matrix stops to reabsorb the water travelling through the preferential ways, allowing some kind of connection of the network, leading to the fast moistening of SM 40cm. The presence of many patches of soil with high repellent characteristics concentrates water movements in restricted areas of the soil enhancing the velocity of travelling through the preferential ways. At this stage, the deeper layers SM 60cm and SM 80 remain to be slowly moist by percolation of the water through the matrix or through an unconnected network of macropores leading to the re-absorption of the water by the matrix.

As SM 40 cm attains the threshold of 35% (simultaneously with a rainfall intensity peak) starts the extremely fast moistening of SM 80cm that achieves saturation in less than 15 minutes (if we considered an infiltration capacity of 30mm per hour, it represents a water circulation 104 times higher than normal percolation velocity of water in the matrix). Mosley (1979) also demonstrated that response time and lateral fluxes rate of subsurface flow on steep forested hillslopes could be fast enough to be a main contributor to channel stormflow in headwater catchment. Water moving in the soil 300 time greater than the measured soil hydraulic conductivity. After saturation of SM 80cm, only half an hour is necessary to saturate SM 60cm.

Globally, circulation of water through the soil profile becomes extremely fast after the SL 20cm and SM 40cm reaching field capacity. It allows the connection of a network of small vertical macropores, and the free circulation of the water in this macropores network. The fast circulation of water for SM 60 cm and SM 80cm seems to be possible without these soil layers reach field capacity. Possibly through a network of vertical macropores, that canalizes directly the water to the soil bottom, leading to the saturation of the deeper layer and then the quick rise of the water table.

These findings are compatible with the model proposed by MacDonnell (1990), where rainfall infiltrated quickly in depth via vertical cracks as rainfall intensity exceed soil surface ks, then the water perches at the soil bedrock interface, and “back up” to the newly saturated matrix. Once free water exists, larges pipes in the lower soil zone quickly dissipate transient water tables laterally, producing a rapid response downslope. Sanda and Cislerova (2009) observed for soil moisture content closed to saturation, fast infiltration of the water by preferential pathways, the saturation of soil profile above soil bedrock interface and the rapid formation of subsurface flow.

Direct field observations of the trenches during the wet season reveal the presence of large areas completely dry and severely water repellent while soil moistures sensors closed to the trenches indicated a soil moisture profile close to saturation. Gosch (2012) for the same study area, by the mean of brilliant blue water infiltration experiments, find out that soil moistening throughout the soil profile is highly heterogeneous presenting patches of almost dry soil close to saturation areas. The remaining of large dry soil patches throughout the entire soil profile during the wet season concentrates the water circulation in other localized areas leading to the generation of processes, normally requiring soil closer to saturation, in response to reduced rainfall amount. The event of 24/12/2013 illustrates this phenomenon, soil moisture sensors indicates a saturation of entire soil profile after 60mm of rainfall, when the theoretical necessary amount of rainfall required was about 100mm.

5.5. Conclusions

The main conclusions of this study are divided following the water fluxes processes.

Overland flow processes for regrowth eucalypt plantations happen following 2 different mechanisms:

- During the dry season, the Hortonian process is the main mechanism of overland flow production. Overland flow is produced locally very frequently as a result of strong SWR characteristics at the soil surface, however the total amount is very low due to re-infiltration downslope into a large network of preferential ways.
- During the wet season, hortonian overland flow already happens exceptionally for very high rainfall intensity peaks. More commonly, overland flow is generated by saturation excess, for events happening under high antecedent soil moisture conditions and high rainfall intensity, particularly as return flow. Overland flow

production is spatially heterogeneous, two plots produce less than 0.1% of annual overland flow, and the last plot reaches 5.75%.

- Subsurface flow is originated both by matrix flow and pipe flow at the soil-bedrock interface, produced mainly during the wet season by matrix flow and exclusively during the wet season for pipe flow. Matrix flow is correlated with soil moisture content,
- A threshold of 25 % of soil moisture for SL 40cm is needed for matrix flow generation, while soil matrix saturation is not a requirement.
- Matrix flow discharge is closely correlated with an increase in soil moisture content.
- Pipe flow generation for medium soil moisture content is delayed when compared with the matrix subsurface flow. It starts with the saturation of the soil bottom, while the more superficial soil layers do not attain saturation.
- Pipe flow discharge is influenced by rainfall intensity.
- Pipe flow discharge persists longer than matrix flow, until all free water is drained and then stop suddenly.
- Pipe flow response to rainfall input for wet antecedent soil moisture content, is almost instantaneous, prior the matrix flow and doesn't require saturation of the soil bottom.

Stream flow response is highly correlated with matrix flow behaviour in timing and intensity.

SWR characteristics influence the behavior of water fluxes in soil. It concentrates the fluxes to some preferential pathways, inducing a very patchy moistening of the soil through the entire profile. This concentration of the water origins an acceleration of the water movement through the soil, almost 100 times greater than normal percolation of the water in the matrix.

5.6. References

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Chapter 6

General conclusions and future perspectives

Chapter 6. General conclusions and future perspectives

This chapter aims to provide an overview and integration of the main findings of each chapter, contributing with informative perspectives. It takes into account the key objectives of the thesis and how they evolved.

The first objective of the thesis was to describe and analyze the temporal patterns in overland flow (OLF) processes in the context of a complete cycle of production of a eucalyptus plantation and in a pine plantation. Chapter 2 responds partially to this objective by presenting a manuscript of a paper focusing exclusively on Eucalypt plantations. To correct to this lacuna, the temporal pattern in term of overland flow production of pine plantation will be presented as additional data to the thesis (table 1).
The paper focuses on annual and monthly patterns of overland flow generation in particular, the role therein of rotation cycle (RC) and, within each cycle, time-since-the-last-disturbance and rainfall volumes. The first specific objective was to determine the overall differences between the three subsequent rotation cycles.
It was demonstrated that multi-year and annual overland flow amounts tended to be limited, typically remaining below 10 % of the incident rainfall. At the level of multi-years OLF analysis, overall OLF coefficients decreased markedly from the first (7.8%) to the second (2.3%) and the third rotation cycle (0.4) Within-site variation was noticeable, as minimum and maximum total OLF amounts differed by factors of 24, 5 and 2 for the three rotation cycles respectively.
At the level of annual OLF analysis, inter-annual variation in site-wise <u>median</u> OLF amounts was substantial in that minimum and maximum annual figures ranged from a factor 3 (RC3) and 5 (RC1) to a factor 12 (RC2). In absolute numbers (mm), the differences between site-wise minimum and maximum annual figures decreased markedly with rotation cycle and, thus, with the strength of the overall hydrological response, from 109 (RC1) to 63 (RC2) and 6 mm (RC3). These differences corresponded to annual OLF coefficients in the ranges of 2.3-9.3, 0.5-3.8 and 0.2-0.5 %, respectively. Within-site variation in annual OLF amounts produced by the three replicate plots at each site was consistent through time and most consistent in the case of the first rotation cycle.

The second specific objective was to analyze the inter-annual patterns of these three rotation cycles. The inter-annual variation in median overland flow amounts appeared to be linked to differences in annual rainfall totals, at least at the first and second rotation sites with Pearson correlation coefficients (r) of 0.80. Time-since-last-disturbance played a perceivable role at the first rotation cycle (i.e. years-since-soil-mobilization) but not at the second rotation cycle (i.e. years-since-logging). This role of years-since-soil-mobilization was also suggested by the site's median annual OLF coefficients. They were clearly lower during the last two than first four hydrological years (2.9-3.7 vs. 6.4-9.3 %) and were strongly, inversely related with years-since-disturbance (Pearson r of -0.80).

The third specific objective was to analyze the seasonal variation (monthly). The study demonstrates that the role of rotation cycle in site-wise median monthly OLF amounts was remarkably consistent throughout the study period. The site-wise median OLF amounts were higher at the first-rotation site than at the second and third rotation sites for 63 out of 67 months. Possibly, the outstanding OLF amounts at the second-rotation site were related to exceptionally high (cumulative) rainfall amounts.
The site-median monthly OLF amounts were better related to monthly rainfall volumes at the third-rotation site than at the other two sites. The respective Pearson correlation coefficients were 0.84 and 0.61 / 0.62, respectively.
The relation of overland flow to time-since-soil-mobilization was very weak (Pearson r = -0.21) and practically non-existent at the second-rotation site as well (Pearson r = -0.08)

Thus overall it can be concluding that:

- multi-year and annual overland flow amounts in the monitored eucalyptus plots tended to be limited, typically remaining below 10 % of the incident rainfall;
- rotation cycle played a marked role in overland flow generation at monthly to (multi-)annual resolutions but this role was more noticeable from the first to the second rotation cycle than from the second to the third cycle;
- time-since-disturbance appeared to reduce annual and monthly overland flow generation but only during the first rotation cycle and, then, not at all plots and in a dichotomous rather than gradual manner, possibly controlled by some threshold in protective soil cover (litter or ground vegetation or both);
- the OLF response of replicate plots tended to vary considerably within study sites but these within-site differences did not always have obvious explanations, arguably including because of a lack of ancillary information on bare cover, root frequency, ground vegetation cover…
- annual but especially monthly rainfall totals could explain reasonably well the temporal variation in site- as well as plot-wise overland flow amounts, even if with the exception of several plots.

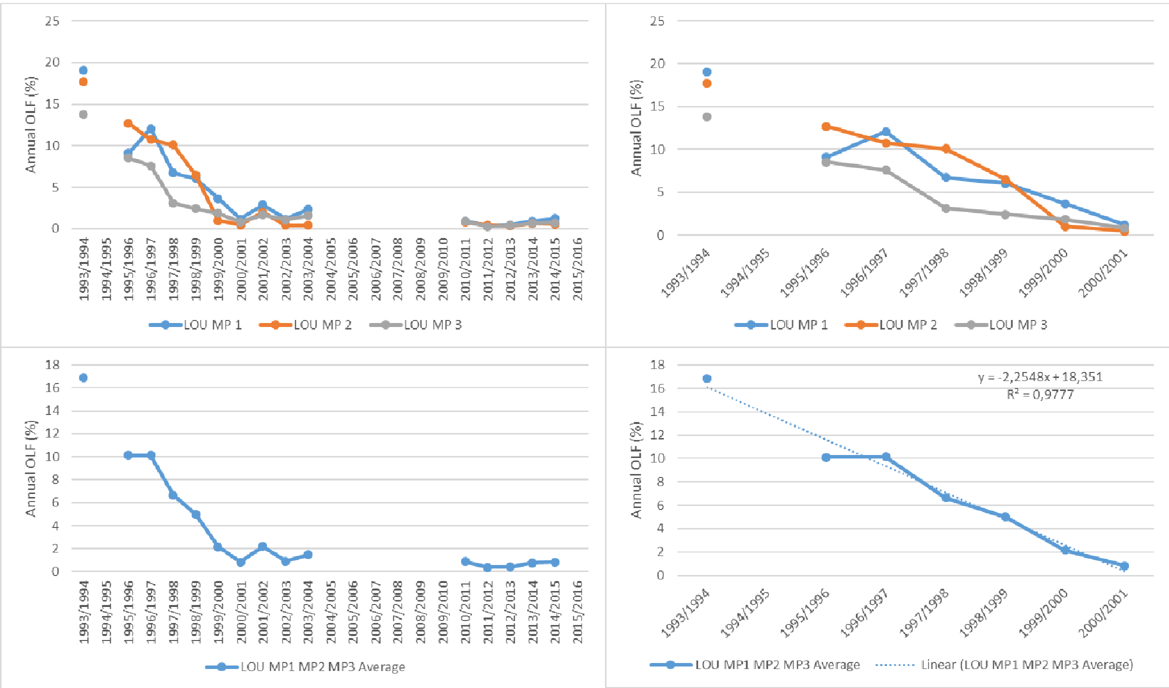
The study of OLF pattern generation in Pine Plantations was assessed in the base of 3 OLF Macroplots of 16m^2, similar to the Macroplots used for eucalypt plantations. There were installed in 1992 in a plantation that burned 1 year earlier in 1991, logged some months after the fire and regenerated naturally. The annual OLF amounts and rates for the 3 plots are presented in the table 1 and figures 1 of the Annex. The first hydrological year with a complete annual OFL dataset considered in the analyses is 1993/1994, with subsequently two decades of record until 2014/2015.

CHAPTER 6

TABLE 1. ANNUAL OVERLAND FLOW AMOUNT AND RATE EVOLUTION FOR 3 MACROPLOTS (MP1, MP2, MP3) FOR PINE PLANTATION (LOU)

		1993/1994	1994/1995	1995/1996	1996/1997	1997/1998	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003	2003/2004	2004/2005	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015
LOU MP 1	(%) OLF	19,1		9,1	12,1	6,7	6,1	3,7	1,2	2,9	1,2	2,3							0,9	0,4	0,5	0,9	1,3
LOU MP 2	(%) OLF	17,7		12,7	10,7	10,1	6,5	1,0	0,5	2,0	0,4	0,4							0,8	0,5	0,3	0,6	0,6
LOU MP 3	(%) OLF	13,8		8,5	7,6	3,1	2,4	1,9	0,8	1,7	1,1	1,6							0,9	0,3	0,4	0,7	0,7
Average		17,7		9,1	10,7	6,7	6,1	1,9	0,8	2,0	1,1	1,6							0,9	0,4	0,4	0,7	0,7
Years since regeneration		2		4	5	6	7	8	9	10	11	12							19	20	21	22	23
Annual Rainfall (mm)		1353		1805	1536	2266	995	1625	3254	1111	2049	1403							1520	1192	2049	2465	1554
LOU MP 1	(mm) OLF	258		165	186	153	60	60	39	32	24	33							14	5	10	23	20
LOU MP 2	(mm) OLF	239		229	165	229	65	16	16	23	9	6							12	5	7	16	9
LOU MP 3	(mm) OLF	187		154	117	71	24	30	27	19	22	23							13	4	9	17	11
Average		239,4		164,5	165,0	152,7	60,4	30,3	26,8	22,7	22,3	22,9							13,3	4,7	8,6	17,5	11,4

FIGURE 1. *ANNUAL OVERLAND FLOW RATE EVOLUTION A) FOR 3 MACROPLOTS INDIVIDUALLY (MP1, MP2, MP3) FOR ALL THE STUDY PERIOD B) FOR AVERAGE 3 MACROPLOTS FOR ALL THE STUDY PERIOD , C) FOR 3 MACROPLOTS INDIVIDUALLY (MP1, MP2, MP3) FOR THE FIRST 8 YEARS OF THE STUDY PERIOD D) FOR AVERAGE 3 MACROPLOTS FOR THE FIRST 8 YEARS OF THE STUDY PERIOD*



At the level of multi-year OLF analysis, median values for the 3 plots decreased markedly during the first 10 years since logging. Median OLF decreased from 17.7% at the third year since logging to less than 2% at the tenth year-since-logging. Then after 20 years since logging, OLF rate was constantly below 1%. Within-site variation was significant. Plot 3 produced consistently one third less OLF than the two other plots. Plot 1 and plot 2 do not show any consistent pattern.

The inter-annual pattern of the pine plantation, in contrast to the eucalypt plantation does not appear vary with annual rainfall amount. Pearson coefficients remain below 0.1 for the 3 plots. Nevertheless, if considering only the 5 last years of study (20 to 25 years since logging), there is a significant positive relationship between median OLF amount and annual rainfall with a Pearson correlation coefficient of 0.71.

In fact, the inter-annual variations in median OLF amount and rate are clearly linked to years since logging. The Pearson correlation coefficients for the 25 years dataset are respectively -0.76 and -0.74. Considering solely the first 12 years since logging, the Pearson correlation coefficients increase respectively to -0.93 and -0.92.

- OLF production in regenerated pine plantations is closely inversely linked to the number of years since logging for young plantations (until 12 years old) but directly related with annual rainfall amount for mature plantation more than 20 years old.
- The median OLF rate decreased from 17,7% at the third year since logging to less than 2% at the tenth year since logging. Then after 20 years- since-logging, OLF rate is constantly below 1%.

The second main objective of the thesis was to determine the influence of forest management practices on overland flow generation and soil moisture pattern using 3 different measurement methods and comparing the results. Three successive eucalypt rotation cycles were studied at two different plot scales (microplot and macroplot) and with two rainfall types (natural rainfall and simulated Rainfall).

The first specific objective was to establish overall OLF values for each measurement method adopted.
Overall OLF values measured at the three successive eucalypt rotation cycles differed with the measurement method adopted. At the microplot scale, natural and simulated rainfall measurements presented a similar temporal pattern of overall OLF rate with the plantation age. In both cases, there was a clear decrease in OLF rate between the first rotation (R1) and the second rotation (R2) from 23% to 15% for natural rainfall and from 40 to 32 % for simulated rainfall. A slight increase in OLF rate between R2 and R3 is also registered for both methods, from 15% to 17% for natural rainfall and from 32% to 33% for simulated rainfall.
Nevertheless, the rainfall type influenced clearly the overall OLF rate; simulated rainfall produced OLF rate twice as high than with natural rainfall for the 3 eucalypt rotation cycles.
At the microplot scale, the rainfall type (natural or simulated) influences the results in term of overall OLF amount, but does not influence the temporal pattern of OLF generation iwithn function of plantation ageing.
These findings confirmed that rainfall simulation experiments are suitable methods to provide information about variability between plots under natural rainfall even if they do not produce the ratios of OLF produced by natural rainfall.

The measurement of OLF production at two different scales, macroplot of $16m^2$ and microplots of $0.25m^2$, during the same period, for natural rainfall, showed large discrepancies in the results.
Measurements with larger plot size produced lower OLF rates than for small plots and the two scales showed different temporal patterns. Thus, at the macroplot scale, annual OLF

rates are significantly lower than at the microplot scale (7% vs 23% for R1 ; 4.8% vs 15% for R2 and 0.5% vs 15% for R3) In the case of macroplot scale measurement, OLF rate decrease gradually with the plantation aging, which is not the case for microplot measurements.
The two methods, macroplot and microplot scale, however were able to capture the general trend of OLF rate through time. The differences maintained proportionality through time. Even for the R2 plantation, that presented a different behaviour, both methods were able to show these differences.

In general, both scales and rainfall types demonstrated that R1 plantation always presented higher OLF rates comparatively to R2 and R3. The plantations R2 and R3 exhibited similar OLF rates at the microplot scale with both natural and simulated rainfall. Plantation R3 had a much lower OLF rate than R2 at the macroplot scale.

The second specific objective of the study was to determine and compare the seasonal variation of OLF at the two scales.
The seasonal OLF amounts increased during the wet period for both methods. The seasonal OLF rate followed the same temporal pattern at macroplot and microplot scales for the 3 three eucalypt rotation cycles. Both scales registered an OLF rate increase during the dry season for R1 and R3, with larger disparities at microplot scale as R2 showed an inverse tendency for the two scales of measurement. The overall percentage of OLF produced during the wet season at R1 and R3 are quite similar at both scales (60% vs 65% at R1 and 63% vs 58% at R3). Nevertheless, R2 presented a large dichotomy of OLF production between wet and dry season, more accentuated at macrolplot scale (91 vs 9%) than at microplots scale (74 vs 26%).

The third specific objective was to identify key factors in OLF generation, with special attention on soil moisture dynamics for each methodology.

At the microplot scale for simulated rainfall, both topsoil stone content and vegetation height showed direct correlations with OLF coefficient. SWR at soil surface and at 0-5 cm depth were also good explanatory variables of the overall OLF values. Mean initial SM contents had also an influence on OLF amount and on the soil moistening patterns. In fact, the rainfall simulation experiments performed on drier soils (inferior to 5%) produced generally higher OLF amounts and lower soil moisture increases than the RSE´s performed over wetter ones.

At the microplot scale for natural rainfall, only litter cover and vegetation depth were found to be marginally negatively correlated with the overall OLF figures. Any other correlation was found at the level of soil moisture or SWR.

At the macroplot scale for natural rainfall, overall OLF amount decreased with time from ploughing and soil penetration resistance. Despite its marginal significance, direct correlations were found between annual OLF figures and vegetation cover, stone cover and soil moisture at 10-20cm depth.

Combining macroplot and microplot scales highlights a negative relations between OLF vs plot scale, OLF vs litter cover and OLF vs vegetation depth, and the positive between OLF vs shear strength.

- In terms of key factors, plot length has the most significant effect on OLF rate due to the higher spatial and temporal variability of infiltration for larger plots. Plantation ageing is the second most important factor, the R1 plantation presenting in any case the higher OLF rate. Soil moisture content is the main factor driving temporal pattern of OLF. Stone cover exhibited a positive relationship with OLF rate and amount. A negative relation exists between litter cover and OLF; the litter plays an important buffer effect.

In terms of soil moisture pattern, soils at the three plantations exhibited extremely low overall soil moisture content not only at the soil surface but also at the deeper layers. Soil moistening was slow and soils only remained moist in long rainy periods. Soil is very permeable and presents a very fast drainage capacity. In fact, the presence of large areas of soil of high SWR down the soil profile leads to a quick circulation of water through preferential ways (e.g. macropores and root channels). Soils also have therefor a low retention capacity. Regular soil matrix moistening is rare due to the presence of large areas with severe SWR characteristics down the soil profile. The driest layer is situated at 20cm depth and is the layer with the higher root frequency.

- Soil Moisture content is a key factor influencing OLF production. During the dry season, the appearance of SWR with soil drying leads to a significant increase in OLF rate at microplot and macroplot scale for the R1 plantation. Nevertheless, due to the reduced amount of rainfall in summer time, this doesn't increase significantly the overall OLF amount. During the wet season the three plantations record higher amounts of OLF at both scales. At the microplot scale OLF amount are more even distributed through time. At the macroplot scale it is concentrated in extreme events, corresponding to saturation OLF conditions.

The third main objective was to analyze the streamflow behavior of the two forested catchments (dominated by eucalypt stand or Pine) and identify the driving key factors.

The first specific objective was to characterize rainfall pattern and the hydrological response in term of streamflow of the two catchments.

The study area experiences high inter-annual variability in rainfall. The wettest year was twice a rainy as the driest year with a prevalence of wet years during the study period. There is a predominance of winter rainfall (41%), followed by autumn rainfall (24%), spring (24%) and a very dry summer (5%).
In general, high annual rainfall is associated with a proportional increase in frequency of significant events and in total hours of rainfall rather than an increase in event duration or rainfall intensity.
The number of large rainfall events > 60mm is relatively low (14%), but represents 43% of the annual precipitation amount. Half of annual total rainfall amount in concentrated in a few intense rainfall events.

The annual streamflow amount (Q) varies by a factor of 6.5 between years, the pine catchment (LOU) presenting a larger variation than eucalyptus catchment (SDC).
The runoff coefficient is higher for wetter years with a maximum of 58% for LOU and 61% for SDC and decreases substantially for the driest year to 17% for LOU and 22% for SDC.
Annual evapotranspiration (ET) amount was relatively constant through the six years of study and not influenced by the total rainfall amount. The average ET of Pine catchment LOU (907 mm) is much higher that for eucalyptus catchment SDC (739mm) indicating the importance of forest type, pine consuming much more water than eucalypt stands.
In term of separation of annual total streamflow (Q) between base flow and storm flow, base flow represents 60% of the Q for LOU and 52% of the Q for SDC.
Soil moisture content is significantly higher and with more variable for LOU than for SDC. Both are related with 3 days API.

Considering the seasonal behaviour of Q on average for all the study years, only 15% of the Q occurred during the autumn as 30% of the annual precipitation amount fell during this season, which has a Runoff Coefficient of 23%. It’s during the winter, the wettest season (41% of the annual rainfall amount) that the streamflow response is the most important, half of the annual Q flowing during this period corresponding to a RC of about 67%.

The second specific objective was to identify correlations between streamflow of the catchments and rainfall amount and distribution, evapotranspiration, soil moisture, overland flow, and land cover.

There was close positive linear correlation between the annual rainfall amount (R) and the total streamflow amount (Q). SDC exhibited a still better correlation than LOU. It is not the case for Runoff coefficient which shows a poor correlation with annual rainfall amount for both catchments.

The seasonal behaviour of Q differs with annual rainfall amount, particularly in autumn. Thus, at the beginning of the wet season, a threshold of about 200mm of cumulative rainfall amount is necessary to produce a significant response in term of streamflow. The dry year exhibited a very low Runoff coefficient about half that for normal and wet year corresponding to a very low Q.

Average years show most rainfall during autumn leading to a large increase of the RC during this season, but the autumn RC is lower than winter RC.

Wet years experienced most precipitation during winter (half of the annual total amount), and it is during this period that 60% of the annual Q occurs, with a very high RC of about 70%.

ET amount was almost constant over the six study years. A reduction in annual rainfall amount leads to a decrease in Q amount, and RC will then decrease proportionally to the annual rainfall amount reduction.

Soil Moisture content and SC showed a good correlation with an even better correlation for LOU, indicating that soil moisture content influences the RC of the catchment.

Monthly overland flow amount showed Spearman correlation coefficients of about 0.48 for RC1 plantation and 0.53 for RC2 plantation with streamflow amount (Q), with these correlations increasing to 0.51 for RC1 and 0.61 for RC2 if associated with the stormflow component.

Monthly overland flow percentage only showed a significant Spearman correlation (0.34) with monthly streamflow, for RC2, with a correlation coefficient of only 0.04 for RC1.

The fourth main objective of the study was to establish the relationship between water fluxes (overland flow, subsurface flow and streamflow) with special attention given to soil moisture behaviour, in a catchment dominated by Eucalyptus plantations.

The first specific objective was to identify the behaviour of the hydrological processes for contrasting antecedent soil moisture conditions.

The main conclusions of this part of the research are presented for each process.

Overland flow processes in regrowth eucalypt plantations were found to follow 2 different mechanisms:

- During dry season, Hortonian overland flow is the main mechanism of overland flow production. Overland flow is produced locally very frequently due to the strong SWR characteristics at the soil surface, but the total amount is very low due to re-infiltration downslope of the water through a large network of preferential pathways.
- During wet season, Hortonian overland flow only happens exceptionally during very high rainfall intensity peaks. More commonly, overland flow is originated by saturation excess, in events occurring under high antecedent soil moisture conditions and high rainfall intensity, particularly as return flow. Overland flow production is spatially heterogeneous; two plots produced less than 0.1% of annual overland flow, whereas the last plot reaches 5.75%.

Subsurface flow was found to occur as matrix flow and pipe flow at the soil-bedrock interface, produced principally during the wet season for matrix flow (throughflow) and exclusively during the wet season for pipe flow. Matrix flow is correlated with soil moisture content.

- A threshold of 25 % soil moisture at the soil layer situated at 40cm depth is necessary for matrix flow initiation, and saturation of the soil matrix is not required.
- Matrix flow discharge is closely correlated with soil moisture content increase.
- Matrix SSF discharge is also closely correlated with streamflow discharge, in term of timing and in terms of intensity.
- Pipeflow does not occur for dry soil moisture antecedent conditions.
- Pipeflow initiation for medium soil moisture content is delay relatively to the matrix subsurface flow. It starts with the saturation of soil bottom, without saturation of more superficial soil layers.
- Initial pipeflow discharge is produced by large macropores situated at the soil bedrock interface. The increase of the discharge is produced by the activation of smaller macropores situated higher in the soil profile, confirming than the activation of the pipes is related with the rise of the water table.
- Pipeflow discharge is influenced by the rainfall intensity.

- Pipeflow discharge persists longer than matrix flow, until all free water is drained and then it suddenly stops.
- Pipeflow response to rainfall input in wet antecedent soil moisture conditions, is almost instantaneous, and prior the matrix flow and does not require saturation of soil base.

Concerning Streamflow,

- After dry antecedent rainfall conditions, only the third event produces a response in term of streamflow and it closely matched the rising limbs of its matrix subsurface flow hydrographs with a runoff coefficient of 18.2%.
- After medium antecedent rainfall conditions, streamflow response was much higher than for dry antecedent with an overall runoff coefficient of 55.9 %, There is also a good agreement between the rising limbs of the hydrographs of streamflow and subsurface flow.
- The “wet” antecedent event produced a similar increase in stream flow as the third “dry” event. Overall runoff coefficient was about 23%, half than for “intermediate” event. The rising limbs of the hydrographs of streamflow and matrix subsurface flow agreed remarkably well.
- In a general way, stream flow response is highly correlated with matrix flow behaviour in timing and intensity.

Concerning soil wetting

- For dry antecedent soil moisture conditions with severe SWR characteristics, rainfall infiltration pattern at the soil surface is driven by soil repellence characteristics. Water infiltration is concentrated in some restricted areas (i.e. cracks, stones, roots, macropores…), but is quickly reabsorbed by the soil matrix. Soil moistening of the matrix reduces SWR severity at soil surface and soil moisture infiltration pattern becomes more homogeneous at soil surface, in some hours or days depending of the rainfall amount.

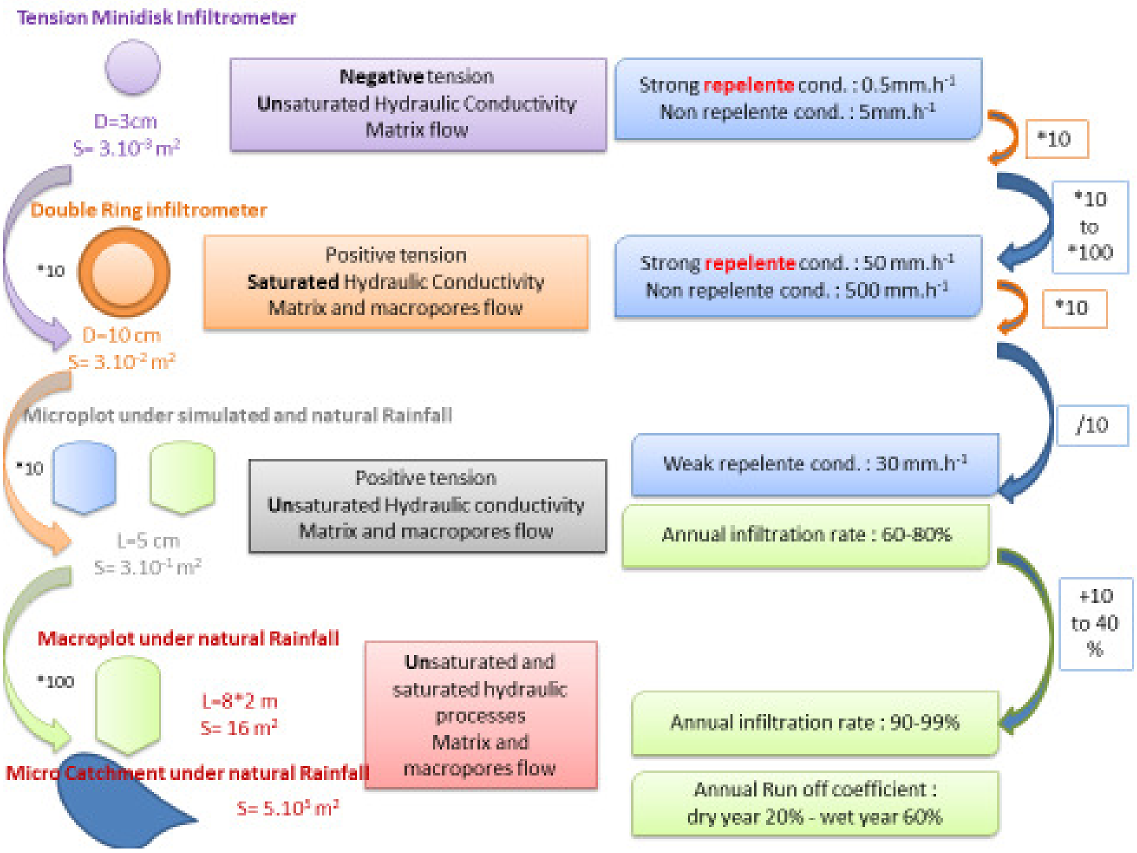
Water infiltration for the deeper layers follows a different behaviour.

- The presence of many patches of soil with high repellent characteristics concentrates water movements in restricted areas of the soil enhancing the velocity of travel through the preferential pathways. When some thresholds of soil moisture content are attained, soil matrix stops reabsorbing the water travelling through the preferential ways, allowing some kind of connection of the network, leading the fast moistening of the deeper layers.

➢ This concentration of the water in preferential ways origins an acceleration of the water movement through the soil, almost 100 times greater than normal percolation of the water in the matrix.

In terms of scale effect on runoff processes, figure 2, presents a brief sinthesis of the results obtained during the study. The two first scale of measurement (minidisk infiltrometer and double rings infiltrometer) were not presented in the body of the thesis, but are interesting to include in this synthesis. The numbers presented were rounded in order to facilitate the analysis.

***FIGURE 2.** SCHEMATIC UPSCALING OF RUNOFF PROCESSES FOR EUCALYPT STAND*



Infiltration rates for the smaller scale performed with minidisk infiltrometers and measuring matrix flow present a variation of factor 10 between measurements performed for repellent and non-repellent soil, respectively 0.5mm/h and 5mm/h. At this scale, only matrix flow method was considered, which obtained very low values.

For measurement performed for a surface 10 times higher with double rings, the velocity of infiltration increased by a factor 100, attaining 50mm/h and 500mm/h for repellent and non-repellent conditions, respectively. The double rings that involve a larger surface of measurement includes cracks and macropores, that enhance locally considerably the infiltration capacity of the soil

For measurement performed for a surface 10 times higher, with rainfall simulation experiments on microplots, for weak repellent conditions, overall infiltration capacity was about 30mm/h and annual infiltration rate between 60 and 80%. For rainfall experiments methods, infiltration rate decreases, as water is not forced to pond at the soil surface as for double rings and part of the water can flow downslope.

For measurement performed for a surface 100 times higher, at the macroplot scale, the annual infiltration rate increase to 90 to 99%m due to the infiltration downslope of overland flow that would be captured and recorded as overland flow at smaller scales.

At the catchment scale, the runoff coefficient is higher for wetter years about 60% but decreases for drier years to about 20 %. The large differences in results shows the importance and influence of the measurement methods and the scale.

This study provides relevant information in term of hydrological behavior of eucalypt and pine plantations that could be helpful in future environmental decision on forest management. It has demonstrated that overall overland flow coefficients decrease with time since logging for both plantation types, attaining a steady state after 12 years, and that successive logging for eucalypt stand does not increase OLF substantially.

The most surprizing finding shown by the data is the evapotranspiration of the mature pine (*Pinus pinaster Aiton*). This is to our knowledge the only dataset for this species, and shows a higher value when compared with the data for the mature *Eucalyptus globulus Labill* stands. This to some extent contradicts the idea commonly accepted in society on the *Eucalyptus globulus* water consumption, and needs to be explored further in order to confirm these findings and permit recommendations in term of Pine plantation management.